The Effects of Seismic Sounds on Marine Organisms:

An Annotated Bibliography and Literature Review

by

Thomas L. Linton, Nadine Hall and David LaBomascus
Department of Wildlife and Fisheries Sciences
Texas A&M University
College Station, Texas 77843

and

Andre M. Landry
Department of Marine Biology
Texas A&M University
Galveston, Texas 77553

October, 1985

TAMU-SG-86-604

Partially supported through Institutional Grant NA83AA-D-00061

to Texas A&M University

by the Office of Sea Grant

National Oceanic and Atmospheric Administration

U.S. Department of Commerce

Price: $3

Order from:

Marine Information Service
Sea Grant College Program
Texas A&M University
College Station, Texas 77843

A/F-4
TAMU-SG-86-604
300 October 1985

Abstract

A literature search has been conducted of experiments dealing with seismic sound sources and their effects on aquatic marine organisms. Researchers report that high-velocity explosives burn rapidly and produce a very fast buildup in pressure which kills fishes. High-velocity explosives that produce a peak pressure of 40 psi kill some fish. Charges as small as 1 pound have been shown to damage fish. The degree of lethality is directly related to charge size and distance from detonation site. Organisms with air bladders, eggs, larvae and juvenile forms were found to be the most susceptible to damage. Low-velocity explosives generate a moderate pressure buildup and relatively low peak pressure, producing relatively no lethal effects to aquatic organisms. Studies have shown that black power charges as large as 1100 pounds producing peak pressures much higher than 70 psi, will not harm fish. Seismic air guns have a moderate pressure rise-time similiar to that produced by low-velocity explosives. Although few studies have been conducted with air guns, they appear to have little adverse effect upon aquatic organisms.

Acknowledgements

The authors wish to thank the International Association of Geophysical Contractors (IAGC) and the Texas A&M University Center for Energy and Mineral Resources for providing the funds for this project. Special thanks are given to the members of the steering committee: Dr. Jim Alexander (Racal-Decca Survey, Inc.), Mr. Dana Larson (Exxon Co.), Mr. Leland Roberts (Chief, Resource Protection Branch, Fisheries Division, Texas Parks and Wildlife Department), and Mr. Bruce Smith (Texas General Land Office). Their assistance was invaluable. Ms. Linda Giffen had the unenviable chore of typing the numerous versions of this paper and Mr. T. Andrew Linton dug in the deep recesses of the library for little known articles on this subject. Their efforts are gratefully acknowledged. Special thanks is due Mr. Charles Darden, President of the IAGC, who was instrumental in the initiation of this project and gave his support from start to finish.

TABLE OF CONTENTS

List of Figures

List of Tables

Introduction

Geophysical exploration is a constantly changing field, with new techniques and substantial innovations occurring frequently. With the vastly expanded search for petroleum reserves brought on by the need for more energy sources there has been even greater modification and revision of these techniques. Many techniques that were commonly used in geophysical exploration only a few years ago have been replaced by faster and more efficient and environmentally satisfactory methods. (See Appendices A,B,C, and D for an overview of explosive energy sources, seismic exploration theory, the nature of underwater explosions, and a description of selected non-explosive energy sources).

In addition to the important oil and gas deposits that are still being sought off the Texas coast there are valuable living marine resources in these areas. In order for both to be utilized on a long-term basis, appropriate safeguards must be incorporated in the regulations that control seismic activities in Texas bays and offshore areas.

Objectives

This project collects and reviews published studies relating to the effects of devices used for sound wave generation in geophysical exploration upon important marine organisms of the Texas coastal waters, including bays and estuaries.

Originally, the review was to be restricted to published accounts of the effects of detonating cord and dynamite upon seven species of special interest: red drum (Sciaenops ocellatus), spotted seatrout (Cynoscion nebulosus), white shrimp (Penaeus setiferus), brown shrimp (P. aztecus), blue crab (Callinectes sapidus), stone crab (Menippe sp.); and the American oyster (Crassostrea virginica). These organisms are of interest because they are the dominant commercial and recreational species taken in Texas waters. This approach was quickly seen to be too restrictive in scope. There have been very few studies conducted concerning detonating cord (such as Primacord). The search has been therefore expanded to locate and include all material, both published or unpublished, relating to the effects of seismic exploration upon fish and aquatic invertebrates.

Literature Review Procedure

Computer and manual searches were used in the literature search. A series of keywords pertinent to the subject was developed (Table 1) and nine systems were queried (Table 2) for publications containing those key words. In addition, the Scisearch (Science Citation Index) system was queried and a manual search was conducted. The manual search consisted of reviews of bibliographies, literature citations from publications, and indices (e.g. Environmental Abstracts, Index of Science and Technology). Unpublished materials were obtained by various methods including telephone communication and personal letters.

Findings

During the past 40 years, many investigators have studied the effects of seismic energy sources on aquatic and marine life. These studies have generally been conducted because of concern expressed by fishermen and enforcement agencies. The following chronological summaries are from the materials obtained through the literature review procedure described above.

(Note: Many of the following references are taken directly from Falk and Lawrence (1973) who published a similar paper).

Table 1

List of Key Words Used

in Computerized Data Base Search

I.	Primacord, Dynamite; Non-Seismic (II-IV)
II.	Seismic, Shallow (and) Coastal Waters, Bay, Gulf, Marine, Estuarine
III.	Fish, Shrimp, Crabs, Oysters, Vertebrates, Invertebrates
IV.	Fish: Black (and) Red Drum, Spotted Sea Trout, Mullet
	Shrimp: White, Brown, Pink
	Crabs: Blue Crabs

Table 2

Primary Material

for

Computer Search and Published Indexes and Abstracts

ASFA (Aquatic Sciences and Fisheries Abstracts)
Biosis (Biological Abstracts and Bioresearch Index)
Enviroline
Environmental Abstracts
Environmental Bibliography
Georef
NTIS (Government Reports, Announcements and Index)
Oceanic Abstracts
Petroleum-geophysical Abstracts
Pollution Abstracts
Scisearch (Science Citation Index)
Sports Fisheries Abstracts
Water Resources Abstracts

I. High-Velocity Explosives

A series of experiments were conducted by Gowanloch and McDougall (1944) to determine the effects of dynamite used in refractive seismic exploration on shrimp (*Penaeus setiferus*), fish (*Micropogon undulatus*) and oysters (*Crassostrea virginica*). Charges of 200 and 800 pounds of 60 percent gelatin dynamite, unconfined and placed on the ocean floor in 18 feet of water, did not harm shrimp at a distance greater than 50 feet and croakers at a distance greater than 200 feet. No mortality in oysters could be attributed to the explosion or its side effects (e.g. silt, gases, etc.). Additional shots of 25 to 400 pounds of dynamite around a natural oyster reef at "various distances" had no adverse effects on oysters.

A series of observations and experiments were conducted in California by Aplin (1947) to determine the effect of 10- to 40-pound charges of 60 percent Petrogel on fish and other marine life. Average calculated mortality counts indicated that about 5 pounds of fish (anchovies, kingfish, sardines, queenfish, and smelt) were killed per pound of explosive used. For shots within the range of 10 to 40 pounds, there was no apparent increase in the poundage of fish killed. Successive shots in the same area continued to kill fish at a constant rate. In general, the greatest number of fish were killed by shots close to shore. This was presumably due to the greater densities of fish in this area. Further, there was no apparent relation between depth of water or charge size and the weight of fish killed. Lobsters were found to be very resistant and suffered no immediate ill effects at 50 feet from a 90-pound dynamite charge. The lobsters were again observed five hours later with none showing any delayed ill effects.

Fitch and Young (1948) conducted studies using high explosive charges that varied in weight from 10 to 160 pounds. They noted different species of fish reacted differently to shock pressures. Barracuda, kingfish and queenfish, having a thick-walled swim bladder and a cylindrical body, appeared to be more resistant to pressure changes than laterally compressed fish with thin-walled swim bladders (e.g. saltwater perch). They also reported that when explosions were repeated (within 24 hours) in the same area, the species composition of the fishes killed was different than those killed by the first explosives. The stomach contents of fish killed during the second day revealed they were feeding on fish that were killed by the first explosions. They also reported that jetted shots (embedded in the sea bottom) killed an estimated 0.23 pounds of fish per pound of explosive and 4.43 pounds of fish per shot. Open water shots killed 0.47 pounds of fish per pound of explosive and 31.56 pounds of fish per shot. Underwater observations along the bottom in this particular study revealed that compared to the number of fish that float, the number that sink is negligible.

Coker and Hollis (1950) observed a series of underwater tests conducted in Chesapeake Bay with shots ranging from 250 to 1,200 pounds of high explosive used for military purposes. Twenty-one shots killed 32,658 fish of 16 different species with menhaden (Brevoortia tyrannus) being the most numerous. Neither the number nor the weight of the fish killed was proportional to the weight of explosive used. Normally the lethal radius did not exceed 600 feet and generally was within 300 feet. Damage inflicted to individual fish was mainly internal including rupture of the swim bladder, vascular system, abdominal cavity and internal organs. It was believed that fish were not driven away from the test areas as a result of the explosive operations. The extent of fish kill was believed to be governed by two factors: (1) rapid dissipation of the explosive force with distance from the shot point and (2) presence or absence of fish within the restricted lethal range. They also felt that surface counts did not account for all the fish affected due to the possibility of sinking fish; however this, was not investigated.

Hubbs and Rechnitzer (1952) in studies using large charges of dynamite (50 - 200 pounds) found them to be very destructive to fish. Charges as small as 10, 5, 2.5, and 1.25 pounds often killed fish, even when the explosive had been buried many feet in the bottom sediments. The lethal effects of small charges of dynamite placed on the bottom were in agreement with the expectation that peak pressure is porportional to the weight of the charge raised to the 1/3 power of the charge weight. For charges buried in bottom sediments, the peak pressure is porportional to the distance raised to the 2.6 power (Figure 1). The effect of underwater explosions of dynamite was often intensified at the surface, where the positive pressure wave reflected as a rarefacted wave. Fish were very susceptible to the negative pressure pulse. They also noted that the lethal range for underwater explosions with dynamite may be greatly extended depending on the shape and nature of the ocean floor (e.g. submarine canyons).

Sieling (1954) conducted studies of reflective type seismic exploration in Louisiana, using nitramon as an energy source. Two experiments were conducted. In the first, oysters were placed in trays on racks that held them slightly above the bottom. In the second experiment, oysters were placed in trays sitting on the bottom. These two experimental arrays of oysters were located at 10, 60, 130 and 250 feet respectively from point of explosion. Four holes, two of 30-foot depth and two of 50-

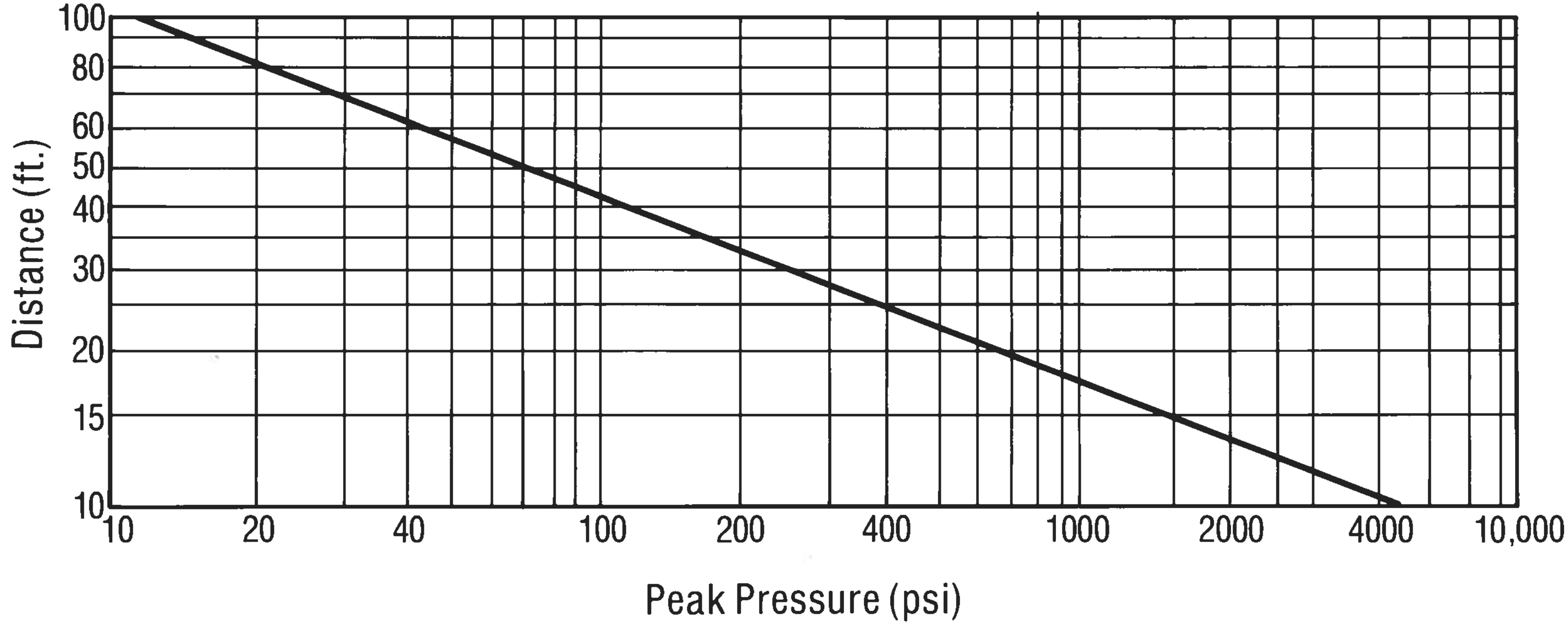


Figure 1. The decay with distance of the pressure from 5 lb. dynamite charges (decreasing inversely as 2.6 power of the distance). (Hubbs and Rechnitzer, 1952)

foot depth, were drilled in the bottom in 10 feet of water. Charges were set with each of the two different hole depths receiving a 20-pound charge and a 50-pound charge. Sieling concluded "no apparent effects were noted on the oysters due to the explosion."

Kemp (1956) conducted studies off the Texas coast on reflective seismic operations using "redfish, pinfish, shrimp, oysters, and crabs." Twenty-foot holes were made in the bay bottom and lined with aluminum pipes. A 40-pound charge (nitramon) was placed in the hole at the 20-foot depth. The test animals were held either in wire cages located on the bay bottom or in cages suspended 3 feet below the water surface. Oyster mortality at the shot-point was found to vary from 10 to 30 percent. Dead oysters were found as far as 200 feet from the shot point. Damage to oysters was most severe within a 25-foot radius. There was no mortality in crabs and shrimp in either surface or bottom cages. Fish were found to suffer a higher rate of mortality near the surface than on the bottom, but beyond a 50-foot radius, fish in the cages "suffered no ill effects".

Hubbs et al. (1960) investigated the effects of underwater Nitro-Carbo-Nitrate explosives suspended just below the surface on caged fish. Cages were placed vertically and horizontally out to 500 feet from detonation site. They found that the peak pressure associated with damage to fish varied among species. The horizontal lethal range was estimated to be 150 feet for a 5-pound charge, 350 feet for a 10-pound charge and 500 feet for a 25-pound charge. Vertically below these shots the lethal ranges were 100 to 140 feet, 140 to 200 feet and 200 to 250 feet for the 5-, 10-, and 25-pound charges, respectively.

An underwater explosion of dynamite was found to be a very effective means of killing adult salmon for tag recoveries (Tyler 1960). Negligible external damage to the fish occurred from the explosions, but there was extensive internal damage. In tests using half-stick charges of 40 percent ammonium gelatin dynamite, a direct relationship was found to exist between water depth and the effective killing range. This range was increased by approximately 15 percent at the 4- and 6-foot depths by doubling the charge strength. It was found that a solid object (deflector) in the path of the pressure wave reduced the lethal range in that direction.

The effect of underwater explosions of Nitrone SM on fish populations in British Columbia coastal waters was studied by Kearns and Boyd (1965). Reflection charges ranged from 5 to 25 pounds and refraction charges ranged from 10 to 300 pounds. Out of 10,676 shots at 9,638 shot points, fish kills were observed at 419 sites. Total surface mortality was estimated to be in excess of 59,300 fish consisting mainly of herring (72.2 percent) and rockfish (23.8 percent). Large Nitrone SM charges (50 - 300 lb) killed more fish than small charges (5 - 25 pounds). By increasing the depth of detonation the potential area of fish kill was increased. Further, in shallow water the horizontal lethal range was greater than that in deeper water.

Paterson and Turner (1968) observed an underwater explosion of 4,000 pounds of NCN explosive in Wentzel Lake, Alberta, Canada. Maximum distance from the blast at which dead or injured fish were found was 1,200 feet. Fish killed were burbot (Lota lota), whitefish (Coregonus clupeaformis), trout perch (Percopsis omiscomaycus) and cisco (Coregonus artedii). The number of fish killed was not stated.

During 1966, the Canadian Department of Energy, Mines and Resources conducted a seismic survey in the Northwest Territories, Alberta, and Saskatchewan, using 1- and 2-ton charges of Nitrone SM and Geogel placed on the bottom (Muth 1966). Estimated mortality ranged from 3 to greater than 10,000 fish consisting primarily of lake cisco, whitefish and lake trout. The lethal radius was estimated to be from 600 to 3,000 feet. Dead or distressed fish appeared at the surface in increasing numbers up to 30 minutes after the explosion. External damage consisted of missing patches of scales, but post-mortem examinations indicated extensive rupture of blood vessels, organs and swim bladder. Blast mortality was not confined to any particular age or size of fish although pike appeared to be the least sensitive. Muth (op. cit.) stated that visible fish mortality was highly variable from lake to lake. He concluded that this was influenced by the proximity of fish to the explosion, pressure differences created by explosions at different depths, the extent of reflected shock waves, and possibly fish that sunk and were therefore unobserved. The latter was not confirmed by underwater observations.

Rasmussen (1967) reported that when dynamite charges were buried in the sea bed, fish mortalities occurred all the way to the surface. For many of the shots, fewer mortalities occurred near the seabed than at the surface. The deadening effect of the seabed was evidently not sufficient to eliminate the lethality of the explosion, even where the bottom consisted of mud and sand. It was found, however, that burying the charge at increasing depths in the sea bed led to a general reduction in the lethal effect. Maximum mortality was observed when the 5.5-pound charges were buried less than 30 feet into the seabed, and little or no mortality occurred when depth of burial was greater than 30 feet. The extent of fish mortality also varied with subterranean features. For example, if a charge was located above a solid stratum the lethal effect was intensified by a large amount of energy being reflected upward. The fact that fish were killed near the surface while those on or near the bottom were not injured was explained in part by the fact that surface and mid-water fish possess swim bladders, whereas bottom-dwelling fish do not. High fish mortality near the surface was also due in part to the rarefacted or reflex wave, which was observed to be especially damaging. Fish killed near the surface in these circumstances usually had their swim bladder burst outward. Further, since the shock wave from a charge detonated in or near the seabed travels in a well-defined cone, expanding toward the surface, a narrow non-lethal zone resulted near the bottom, while fish were killed in an ever-widening area toward the surface.

A series of caged fish experiments were carried out under ice by Roguski and Nagata (1970). They found that the detonation of 130.5 to 142.5 pounds of suspended, high-velocity explosive in water depths of 10 to 20 feet had a 100 percent mortality radius of about 300 feet and a maximum lethal radius of approximately 500 feet for juvenile salmon (two to three fish/cage). Larger charges did not extend the lethal range under these conditions. There was little difference in effect between charges in water depths of 10 and 20 feet, although a charge at an intermediate depth of 15 feet appeared to have a somewhat shorter lethal range. Great variation in damage to fish in the same cage was often noted. One salmon suffered no apparent damage while another might be dead or die later of injuries. They theorized that this possibly was because of differences in position of fish at the time of the explosion, thus resulting in some absorbing more of the shock wave than others.

The effects of elastic waves on the eggs of various species of fish was studied by Kostyuchenko (1971). TNT charges (50g) were used to produce the elastic waves. Eggs were placed in fine wire-mesh boxes at a density of

100 eggs/box. Boxes were placed at distances of 0.5, 1, 2, 5, 10 and 20 m from the firing sites. The TNT charges were suspended 5 m below the surface. Shielding of the eggs by the wire-mesh boxes was judged insignificant. The tests concluded that a 50-g TNT charge damages eggs at a distance up to 10 m (33 ft).

Spears (1980) conducted studies in Texas of refractive seismic techniques using 4.15 pounds of Primacord (detonating cord) 100 feet in length as the explosive sound source. The charge was placed in 10 feet of water on the bay bottom. The test animals, red drum (Sciaenops ocellatus), black drum (Pogonias cromis), sheepshead (Archosargus probatocephalus), blue crabs (Callinectes sapidus) and brown shrimp (Penaeus aztecus), were retained in wire cages at surface and bottom locations. The cages were in a line perpendicular to the Primacord at distances of 5, 10, 25, 50, 75 and 125 feet. No fish or crabs were killed in surface cages beyond 50 feet from the explosion site. No shrimp were killed beyond 75 feet. In bottom cages no fish, crabs or shrimp were killed. Mortality was essentially 100 percent for all animals at distances closer than 50 feet to the explosion at both surface and bottom locations.

II. Low Velocity Explosives

Hubbs and Rechnitzer (1952) found that black powder was much less effective than dynamite in producing reflected waves. Black powder explosions proved to be relatively innocuous to aquatic organisms. Charges of up to 45 pounds, which produced peak pressures as high as 160 psi, did not kill fishes. There were indications that black powder discharges did not drive fish away or prevent them from feeding.

Fry and Cox (1953) observed the effects of black powder charges on fish life along the coast of California. The charges used varied in size from 40 to 90 pounds. After a blast, divers searched the bottom within a radius of 100 feet. No dead or injured fish were found. Also, clams and tube worms endemic to the area apparently suffered no ill effects.

Ferguson (1961) found black powder, fired with an electric squib (detonator), to be relatively innocuous to yellow perch (Perca flavescens fluviatalis). On the other hand, charges of nitrone, a high-velocity explosive, were harmful to perch and other species. Even a 1-pound nitrone charge killed some perch up to 200 feet away. Ferguson noted that fish, held in cages at various distances from the explosion, provided the best measure of charge lethality. There was no apparent difference in the degree of damage between fish in cages at the surface and those at the bottom. The direct distance between the fish and the energy source appeared to be most important. Experiments using black powder detonated with nitrone primers proved to be fatal to fish. Subsequent testing showed that the nitrone primer was the lethal agent.

III. Non-Explosive Sound Sources

Numerous studies have been carried out on the effect of underwater explosions to marine and aquatic life, but there are few reports dealing with the effects of non-explosive energy sources. Gaidry (unpub., in Falk and Lawrence, 1973) found that caged oysters placed in close proximity to a seismic air gun were unharmed. A series of experiments were conducted by Weaver and Weinhold (1972) to determine if the use of air guns in shallow water was injurious to fish. In these tests, caged coho salmon smolts (Onchorhynchus kisutch) were subjected to the firing of 20 to 40 cubic inch air guns at various distances and depths. They concluded that air guns of this size exerted no harmful effects on these fish.

Kostyuchenko (1971) observed the effects of elastic waves on eggs of various species of fish. Non-explosive sound sources used included a seismic air gun (2050 psi) and an electric pulse generator (20 kv). Eggs were placed in fine wire-mesh boxes at a rate of 100 eggs/box and positioned at equal distances horizontally and vertically out to 20 m (66 ft). The tests concluded that the elastic waves arising from the discharge of the air gun and electric pulse generator injure larvae (within the egg) at a radius of up to 5 m (16.5 ft).

Chelminski (1974) stated that in the five years PAR 300-cubic-inch air guns had been used in reflective, refractive and well-velocity surveys there was an "absence" of evidence that they damage fish. Hubbs and Rechnitzer (1952) demonstrated experimentally that black powder has a very small damage radius. They attribute this effect to the impulse characteristics of black powder, primarily the moderate rise-time to peak pressure. Chelminski (op. cit.) therefore concluded that "since air gun and black powder rise-times are similar we surmise that the effects of equal pressure peaks will be similar; that is, they are not serious causes of mortality in fish."

In recent years many non-explosive energy sources have been used for seismic exploration. These energy sources have been adopted for a variety of reasons, including the achievement of better seismographic records and the banning of high velocity explosives by various regulatory agencies and governments.

IV. Discussion

In fishes, it appears that those possessing swim bladders are the most susceptible to damage from high-velocity explosive detonation. Fishes which do not have swim bladders, as well as shrimp, crabs and oysters, have been

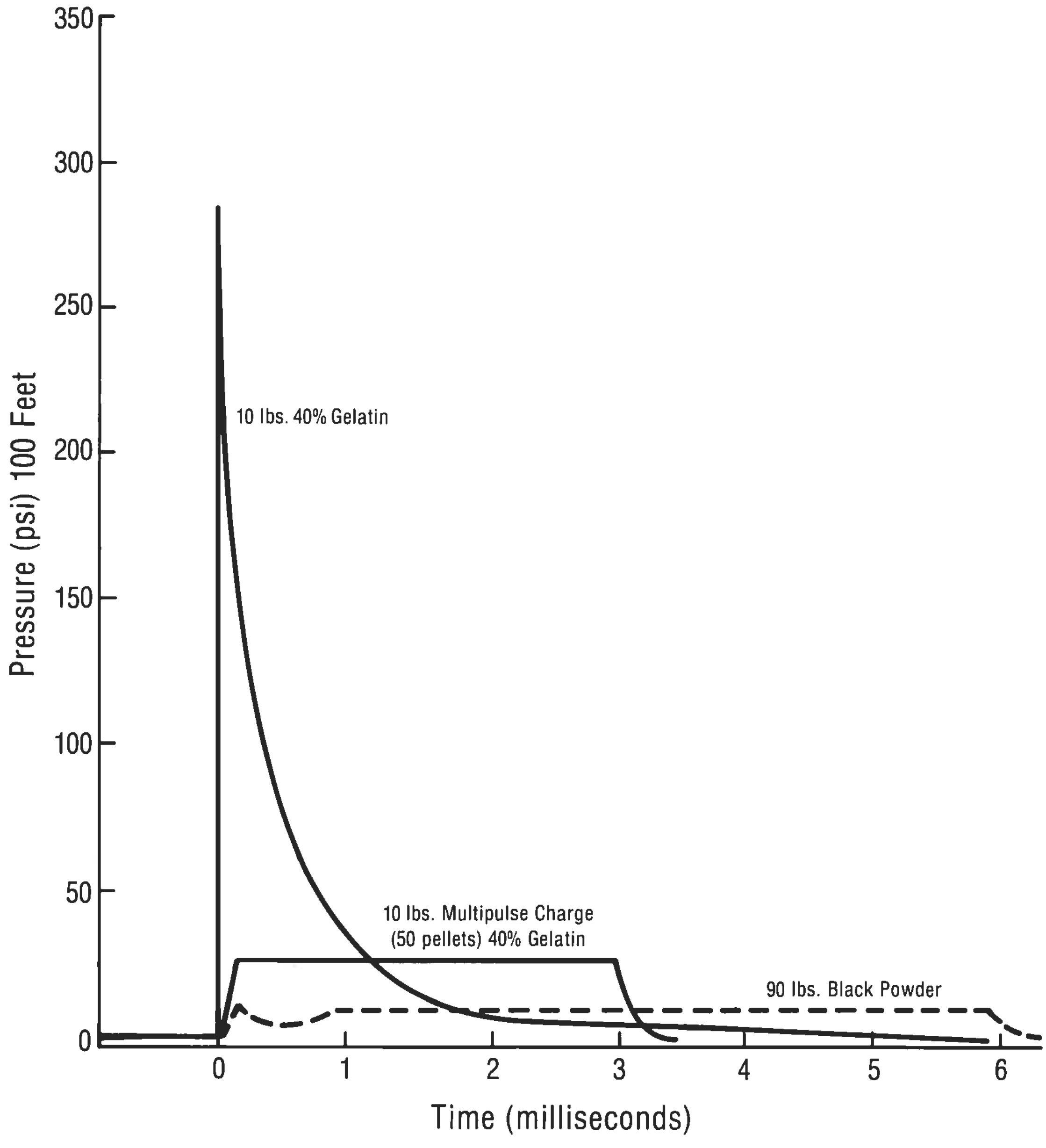


Figure 2. Pressure time curves for ten pounds of 40% gelatin, ten pounds of multipulse, and 90 pounds of black powder, computed to the same base. (Trasky, 1976)

bladders. The damage sustained by fishes with swim bladders appears to be directly proportional to the size of impulse produced by the explosive. Impulse is defined as pounds per square inch (psi) produced by the explosion and the time over which that pressure is produced. A high velocity explosive produces a very large psi of short duration. Figure 2 is a representative graph of a typical pattern produced when a high velocity explosive is detonated. The "spiked" peak produced is the "lethal" component of the blast. The rapid rise and fall in pressure causes the swim bladder of a fish to rupture because it cannot adjust its internal pressure quickly enough to compensate for these rapid changes. It is generally accepted that high velocity explosions producing a peak pressure up to .pn16 40 psi will kill some fish. In those that produce pressure above 70 psi, all fish are killed (Alpin, 1947; Christian, 1973; and Wright, 1980). On the other hand, with a low velocity explosive such as black powder, a sharp peak is not produced (Figure 2). Studies have shown that fishes are able to withstand pressures in excess of 70 psi and survive if no sharp peak is produced (Fry and Cox, 1953; Hubbs and Rechnitzer, 1952; Kogarko, et al. 1975; and Wright, 1980).

Stage of maturity of fishes also modifies the effect of explosives. Eggs and larvae appear to be more susceptible to damage from seismic sound sources than are larger (adult) fishes (Kostyuchenko, 1971; Trasky, 1976; Wright, 1980; and Yelverton, et al. 1975).

Oysters, if not under stress, appear to be able to withstand explosions of high velocity explosives (except within an immediate 25-ft radius) and the other means of producing sound waves in geophysical exploration (Anon. 1976; Gowanloch and McDougall 1946; Kemp 1956; and

Sieling, 1954). Stress is produced when water temperature or salinity is varied over an extended period of time (e.g. under drought conditions or freshwater flooding, etc.).

The only major factor reported to influence mortality of shrimp and crabs is distance from the site of detonation (Gowanloch and McDougall, 1946; Kemp, 1956; Linton et al., unpubl.; Spears, 1980; and Sieling, 1954).

Five particular areas which could be considered in establishing regulations that will govern geophysical exploration are: (1) proximity of the organism to site of detonation; (2) depth at which explosive is detonated; (3) season; (4) behavior of the organism; and (5) characteristics and nature of the shock wave produced and its zone of influence.

1. Proximity of the organisms to site of detonation.

Seismic regulations should contain provisions to insure that explosive seismic sources be such that they do not occur, as a minimum, within the lethal radius of oyster reefs and fish schools. The distance of separation required should be determined by the type of sound source being employed. A recommended minimum distance for various weights of high velocity explosives is 1000 feet.

2. Depth at which explosive is detonated.

The effect of water depth on the lethal range of underwater explosives reported in the literature is somewhat variable. Aplin (1947) concludes that there is no apparent relation between depth of water and the weight of fish killed. Studies on salmon and northern pike by Roguski and Nagata (1970) reveal no direct relationship between lethal range and depth when charges were detonated in water depths of from 10 to 20 feet. They state the difference may be due to differences in propagation of shock waves of charges fired at different depths. Tests conducted by Tyler (1960) however, show a direct relationship between depth and lethal range. Bottom-placed charges, at increasing depths, produced increasing lethal ranges to salmon. Kearns and Boyd (1965) found that an increase in detonation depth increases the potential for fish kill. They present evidence indicating that charges of the same magnitude set to explode at greater depths are more lethal to fish than those exploded at shallow depths. The shock wave from a charge detonated in the seabed or near the bottom travels in a well-defined cone, expanding in area toward the surface. Thus, the greater the water depth, the greater the lethal area from an explosion (Rasmussen, 1967).

Concerning the practice of embedding explosive charges into the sea bottom, the findings are also variable. Fitch and Young (1948) conclude that embedded shots kill less fish while Hubbs and Rechnitzer (1952) find that embedded shots are equally as lethal as open-water shots. Rasmussen (1967) states that a charge buried into the seabed at a depth of 30 feet or more leads to a general reduction in lethal effect.

Although there are contradictory findings in some of the studies, the majority report that charges placed in successively greater depths produce greater lethal ranges.

3. Season

The relative numbers of marine organisms in shallow water (bays) during the four seasons may provide guidance for seismic operations to maintain a minimal occurrence of mortalities. This would reduce the potential for large-scale kills, or adversely affecting eggs, larvae and juvenile forms of marine life. Also, the additionally stressful conditions produced by the extremes of winter and summer should be kept in mind when planning seismic activities.

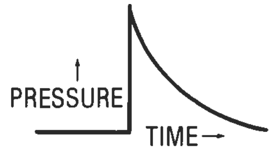
4. Behavior of the organisms.

In reference to the current practice of "employing industry approved methods to drive away marine life in the area to be shot (firing a warning shot)" (Anon, 1978), no information has been located which would indicate that the practice is effective. Hubbs and Rechnitzer (1952) have found that if explosions "stirred-up" bottom sediments, fish could be attracted to the area to feed on the organisms that were dislodged from the sediment. Fitch and Young (1948) state that fish were attracted to an area after seismic exploration to feed on the fishes killed by the charges detonated earlier. Burnes and Moore (1963) have found that fish (brown and rainbow trout) "became conditioned to noise almost immediately." Warning shots are probably of little value in driving fish from an area and may well produce the opposite effect.

5. Characteristics and nature of the shock wave produced and its zone of influence.

The materials reviewed in this project indicate the need for regulations that recognize the inherently different effects upon marine organisms by high-velocity explosives which produce the "sharp-peaked" impulse and other sound sources which do not. Christian (1973) has theoretically determined characteristics of shock waves from underwater explosions, their propagation behavior, and their zones of influence as modified by depth/location of detonation (Figure 3: A,B, & C). These models provide a basis for predicting the impact of seismic exploration that involves use of high-velocity explosives.

A.



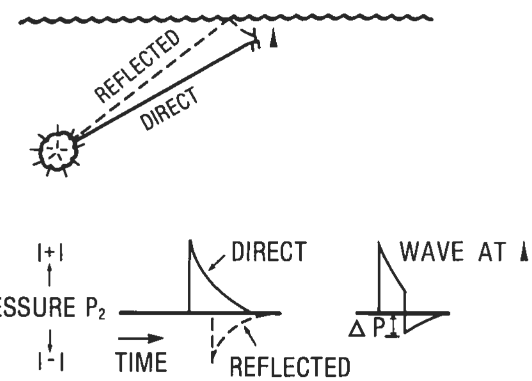
SHOCK WAVE FROM UNDERWATER EXPLOSION

Peak Pressure	$f\,(W^{1/3}/R)^{1.13}$
Duration	$f\,(R/W^{1/3})^{0.22}$

at range of 100 ft.

charge wt.	**peak pressure**	**duration**
1 lb.	120 p.s.i.	0.16 millisec
1000 lb.	1600 p.s.i.	1 millisec

B. DIRECT AND SURFACE - REFLECTED PRESSURE WAVES



C. SCHEMATIC OF DAMAGE ZONES FOR SHALLOW AND DEEP EXPLOSIONS

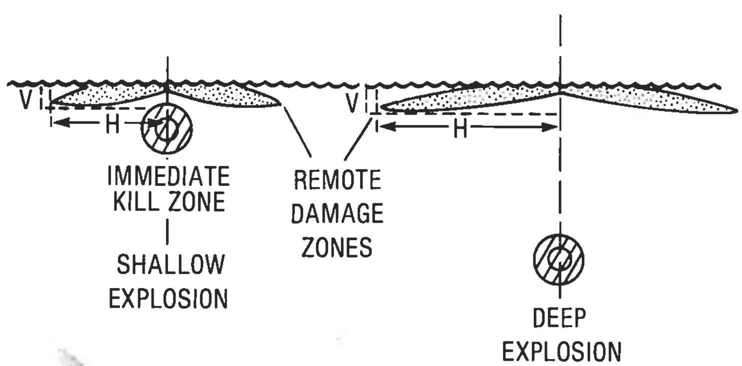


Figure 3. (from Christian, 1973)

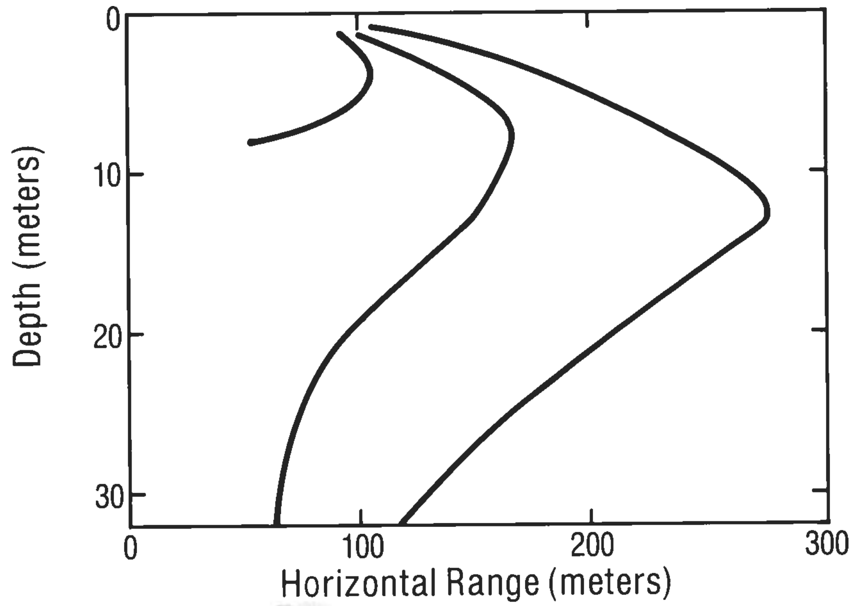


Figure 4. Predicted regions of greater than 10%, 50%, and 90% kill for white perch of 21.5 cm fork length for a 32 kg pentolite charge, at a depth of 9 m and 91 m horizontally from the test fish. (Wiley, Gaspin, and Goertner, 1981)

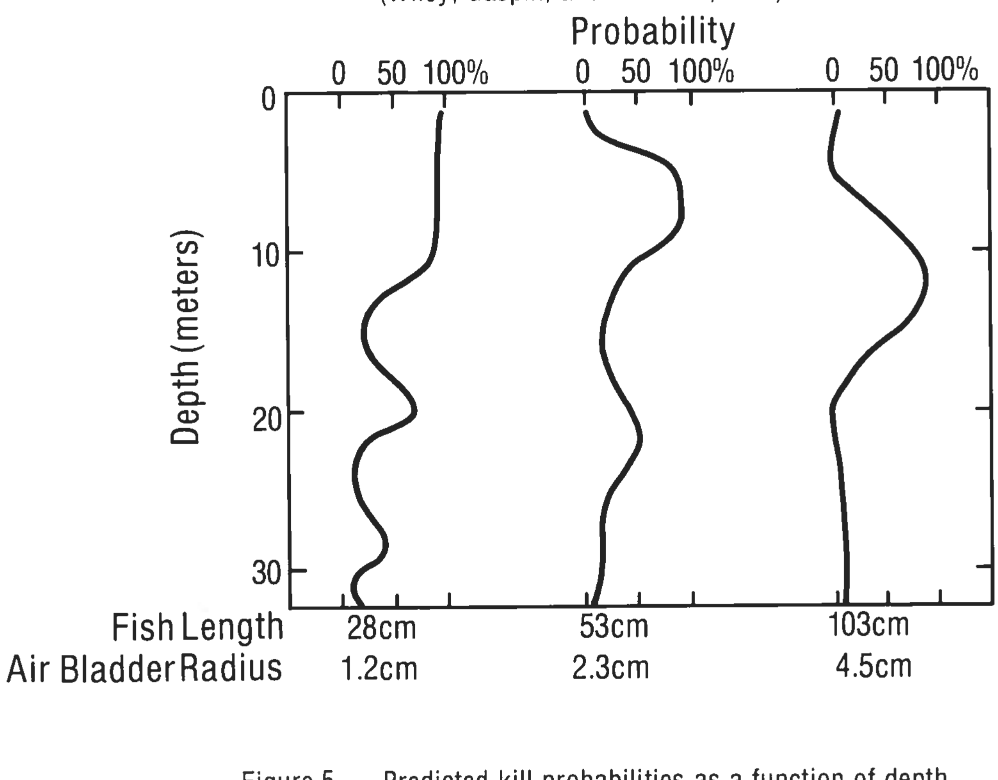


Figure 5. Predicted kill probabilities as a function of depth for different size striped bass; 32 kg pentolite charge at a 9 m depth and 91 m horizontally from the test fish. (Wiley, Gaspin, and Goertner, 1981)

An alternate approach has been proposed by Wiley, Gaspin and Goertner (1981), to predict the probable lethality of an underwater explosion in deep water and the kill distribution for fish (Figures 4 and 5). These models apply only to fish with swim bladders and rely upon the assumption of uniform spatial distribution for each size class and species of fish. The predictive capability is best in deep water.

As a result of the information reviewed during preparation of this report, three models for estimating the maximum lethal ranges of high-velocity explosives, low-velocity explosives, and seismic air guns were constructed. They are based upon findings reported in the literature of weight of charge plotted against distances at which mortalities were observed (Figures 8, 9, and 10 of Appendix E). Prediction can be accomplished simply if the weight or size of the energy source is known. See Appendix E for complete explanation.

Conclusion

A limited number of studies have been conducted on a variety of aquatic vertebrate and invertebrate organisms dealing with the manner in which the most commonly used seismic sound sources affect these organisms. Numerous questions remain unanswered, particularly in regard to air guns.

High-velocity explosives are shown (via the literature) to be lethal to aquatic organisms due to their extremely rapid pressure rise-time. A peak pressure of 40 psi will kill some fish while 70 psi will kill all fish near the explosion. Low-velocity explosives, which produce a moderate peak pressure, are relatively innocuous to fishes. Evidence to date indicates that seismic air guns are "relatively harmless" to aquatic organisms.

There are few studies relating to high-velocity explosive sources and their effects upon shrimp, the number one fishery in the Gulf. None of the experiments reported in the literature could be considered "definitive" in regard to shrimp.

It would also be prudent to better define the "zone of influence" for high explosives. The model provided by Christian (1973) can be a good first step toward that goal (Figure 3).

The reactions of fishes to seismic exploration has been shown to vary. When Primacord is used, the industry recommended practice is to fire a "warning shot" to frighten fish out of the area before exploration work is begun (Anon, 1978). It has been shown that certain fishes become accustomed to sounds in the water and quickly ignore them (Burner and Moore, 1963). This would indicate that the "warning shot" is ineffective. Also, a related matter of dispersion of fish by pneumatic seismic exploration is receiving increased attention in California; commercial fishermen contend that when pneumatic sound sources were used in seismic exploration off the California coast fish schools were dispersed. However in a pilot study of the effects upon "commercially viable plumes (aggregates)" of rockfish, it was found that there were less distinct changes in their spatial distribution in the field than in laboratory experiments (Fish Dispersal Steering Committee, 1985).

The particular area in need of study concerning seismic air guns is their influence upon behavior. The few studies conducted with seismic air guns show them to be relatively harmless to aquatic organisms (see Appendix E). The possible behavioral effects produced by air guns need to be investigated to provide a more complete picture of their influence. A possible method of accomplishing this need is telemetry. Through controlled experiments using telemetry devices, fish could be tracked in the field. Through such tracking experiments, behavioral responses to seismic exploration could be clarified. Telemetry is being used extensively to track the movements of fishes and other aquatic organisms (Minor, 1981; Nelson, 1981; Summerfelt, 1972), and the techniques for attachment, implantation, and recovery are being perfected (Nelson and McKibben, 1981).

One of the major problems concerning the studies reviewed in the literature is the lack in consistency of technique, control and quality. Following are recommendations and considerations that should be included when conducting a study concerning the effects of seismic sound waves upon aquatic organisms:

1. Long term observations (e.g. 7-14 days) to detect delayed mortality.

2. Possible mortality as a result of "stunned" fish that are preyed upon before recovery.

3. Improved use of control organisms (i.e. cage placement and handling).

4. Detailed measurements of: distance of the test organisms from detonation site, depth of test organisms, charge depth, pressure-time, and signature vs. distance.

5. Complete observations of free-swimming organisms which may have been killed or injured by the detonation, including underwater observations for possible sinking fish.

Summary

I. High Velocity Explosives

Internal injury as opposed to external injury is most common in fishes exposed to explosions (Coker and Hollis, 1950; Fitch and Young, 1948; Muth, 1966; and Tyler, 1960).

Fishes with thick-walled swim bladders and cylindrical body shape appeared to be more resistant to rapid pressure change than laterally compressed fish with thin-walled swim bladders (Fitch and Young, 1948). Fish are attracted to an area by fish killed from previous seismic explosions being used as food.

Underwater observations revealed that the number of fish that sink to the bottom after detonation is negligible (Fitch and Young, 1948).

Fish are not driven away from a test area as a result of test explosive (Coker and Hollis, 1950). The extent of fish killed is governed by: (1) rapid dissipation of the explosive force with distance from the shot point and (2) presence or absence of fish within the restrictive lethal range.

Peak pressure varies with one-third the power of the charge weight (Hubbs and Rechnitzer, 1952). Peak pressure from charges buried in bottom sediments varied as the 2.6 power of the distance. Lethal range for underwater explosions with dynamite may be greatly extended depending on the shape and nature of the ocean floor (i.e. rocky submarine canyons).

Rasmussen (1967) found that burying the charge at increasing depths in the seabed led to a general reduction in the lethal effect. Maximum mortality was observed when charges (5.5 pounds of dynamite) were buried less than 30 feet into the seabed and little or no mortality when depth of burial was greater than 30 feet. The extent of fish mortality also varied with subterranean features.

The shock wave of a charge in the seabed or near the bottom travels in a well-defined cone expanding toward the surface (Rasmussen, 1967).

II. Low Velocity Explosives

Black powder explosions are relatively innocuous to fish; charges of up to 45 pounds which produced peak pressures as high as 160 psi did not kill fishes (Hubbs and Rechnitzer, 1952; Fry and Cox, 1953).

III. Non-explosive Sound Sources

Non-explosive sound sources such as air guns, water guns, etc., are reported to have no lethal effects on fish. Seismic air guns have been reported to damage fish eggs at short distances from the source (16.5 feet) (Kostyuchenki, 1973; Chelminski, 1974).

Appendix A

Explosive Energy Sources
(Falk and Lawrence, 1973)

There are many different kinds of explosive energy sources used for seismic exploration. These may be divided into three groups: low-velocity explosive (slow pressure buildup), high-velocity explosive (rapid pressure buildup), and blasting agents. Figure 6 gives a representative comparison of some of these different types of explosives. Black, or gunpowder, is an example of a low-velocity explosive which burns slowly and produces a slow buildup in pressure of the expanding gases. Its detonation speed is approximately 2,000 ft/sec. However, the use of black powder has generally been discontinued due to hazardous handling properties and poor quality of the seismographic records. High-velocity explosives include many grades of dynamite, Tri-Nitro-Toluene (TNT) and other compounds. All burn rapidly and produce a very fast buildup in pressure. The speed of detonation for dynamite ranges from 4,000 to 23,000 ft/sec depending on strength, intensity, and grade. Examples of brand name high-velocity explosives are Geogel, Loshok, Primacord and Aquaflex. The latter two are detonating fuses which consist of a high explosive charge, Pentaerythritoltetranitrate (PETN), contained within a waterproof covering. When initiated by an electric blasting cap, they detonate at a very high velocity (23,000 ft/sec; Anon, 1978). Primacord and Aquaflex are line sources, whereas black powder, TNT, etc. are point sources, and are contained within a waterproof cylindrical cartridge.

A blasting agent is not considered an explosive by itself but can be made to explode by using a primer. Blasting agents are composed of ammonium nitrate and are known as Nitro-Carbo-Nitrate (NCN) explosives. Velocity of detonation ranges from 8,000 to 16,000 ft/sec. An example of a blasting agent is Nitrone SM (Nitrone Seismic Marine).

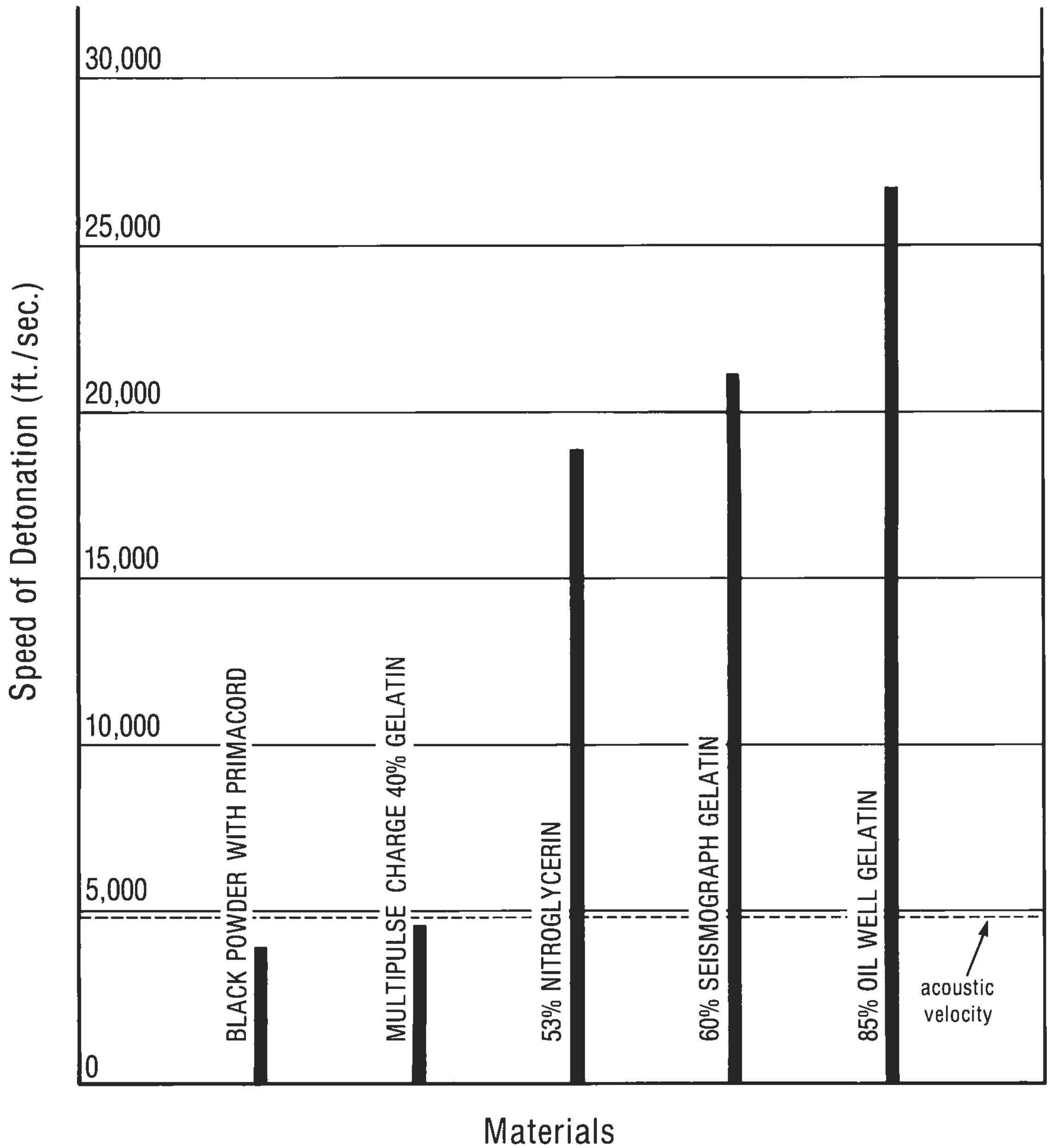


Figure 6. A comparison of explosive velocities for various materials. (Trasky, 1976)

Appendix B
Seismic Exploration Theory
(Falk and Lawrence, 1973)

The principle of seismic exploration is derived from seismology which is the geophysical science dealing with earthquakes and related phenomena (Ewing and Engel, 1962). Through controlled generation of acoustical energy pulses near the surface of the earth's crust, geophysicists are able to locate geological structures which could contain oil and/or gas. When these pulses or vibrations strike a layer of rock or other dense material, they divide into three parts; one part returns to the surface as reflected energy; another travels longitudinally along this layer at a greatly increased speed, with a portion of it returning to the surface as refracted energy. The remaining part which passes downward divides repeatedly as it hits new dense layers. Acoustical energy, returning to the surface, is transformed by a series of geophones into electrical energy which in turn is recorded by a seismograph. Recordings yield a seismic section which is translated into an accurate picture of rock layers beneath the surface.

The sea, where much of the seismic exploration is carried out, provides a uniform coupler with the underlying bottom. Marine seismic surveys, using explosives, are conducted using two methods with minor variations (Figure 7). The refraction method uses the principle that the speed of the shock wave varies according to the elasticity and specific gravity of the rock. Wave speed indicates the depth and type of rock. In the reflection method, shock waves are reflected like an echo when they strike a surface boundary between layers of different elasticity and specific gravity. The depth of the reflecting layer can be determined by measuring the time taken for the waves to travel to and from the reflecting layer. The energy source is small and relatively closer to the recording instruments for reflection shooting, while it is larger and farther away for refraction shooting.

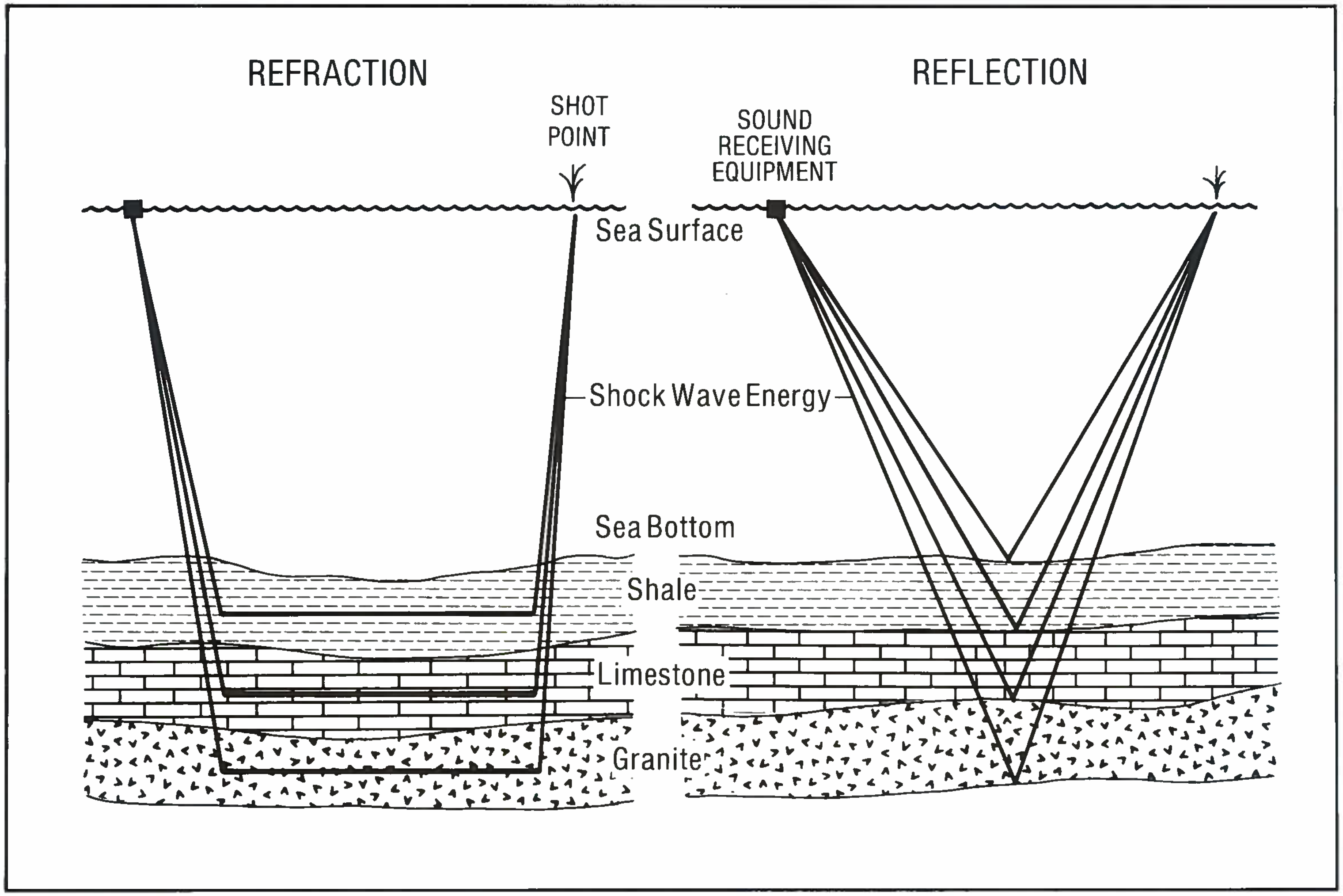


Figure 7. Schematic representation of refraction and reflection shooting. (Falk & Lawrence, 1973)

Appendix C

Nature of Underwater Explosions
(Cole, 1948; Falk & Lawrence, 1973).

The essential characteristic of any underwater explosion is the release of a high initial outward acceleration of energy to the surrounding medium. A substantial portion of the total energy released to the water by a seismic source is not radiated immediately in the form of a seismic wave, but is retained and stored temporarily as kinetic energy in the water. At a predictable time later the outward flow of water is reversed, and inward flow converges to produce a secondary seismic pulse called the first bubble pulse.

Detonation within a solid explosive does not take place instantaneously throughout the entire mass, but proceeds as a wave traveling with finite velocity. The disturbance is in the nature of a chain reaction which travels rapidly outward, creating a growing spherical cavity. The traveling gas-solid interface is known as the detonation front. At a very high pressure, seawater is not an ideal elastic substance. It behaves somewhat like a spring; the more suddenly compressed, the stiffer it becomes. Thus, the velocity of the outward traveling shock wave is a function of the peak pressure of the wave. As an example, the instantaneous peak pressure for 50 pounds of TNT is million pounds per square inch (psi), and the estimated velocity of propagation is 14,000 ft/sec. At a radius of 1 foot the instantaneous peak pressure in the shock wave is 180,000 psi and the velocity 83,000 ft/sec. At a distance of 5 feet, the instantaneous peak pressure is 16,000 psi and the velocity of propagation of the shock wave is 54,000 ft/sec. It is estimated that about 30 percent of the original explosive energy is dissipated as heat in the first 10 feet of travel. The peak pressure initially falls off as the -2.9 power of radial distance (R) at the explosive-water interface. As the shock wave travels outward in the surrounding medium and the peak pressure drops from one million to 16,000 psi, the rate of decay decreases to $R^{-1.3}$ at R=5 feet. As the peak pressure further diminishes with increasing distance, the decay rate approaches $R^{-1.13}$ and remains at this value until the shock wave eventually degenerates into a low amplitude acoustic wave.

All types of underwater seismic energy sources give rise to hydraulic after-flow. The phenomenon is inherent in the nature of the source and in the associated spherical divergence. After-flow represents temporary storage of kinetic energy not immediately radiated. This energy is ultimately dissipated as bubble oscillation. Because of the momentum stored in the outward after-flow of the surrounding water, the gas bubble continues to expand to the maximum radius. Due to cooling and expansion in volume, the gas pressure falls. For a brief period of time, the water surrounding the gas bubble is, because of its accumulated after-flow momentum, actually moving outward against an inwardly directed pressure gradient. This phenomenon is called overshooting. Eventually expansion is halted and the bubble contraction begins, at first slowly, and then with increasing speed. The collapse is in the nature of an implosion, the result of which is a rapidly increasing inward velocity in the water medium, and rapidly increasing pressure due to compression of the gas bubble. Ultimately, the outward directed pressure gradient brings about contraction. From this time on, the process is reversed and the bubble expansion begins again. The cycle may be repeated several times with decreasing intensity -- a phenomenon called bubble oscillation.

At a given distance from the source, the arrival of the shock wave will cause water pressure to rise almost instantaneously, then decrease exponentially to a negative pressure. At this time, corresponding to the start of the bubble contraction, pressure will increase again, at first slowly, and then with increasing speed to the first bubble pulse peak. Pressure will then decrease again starting the second bubble oscillation cycle. Although the bubble pulse is much lower in peak pressure amplitude than the initial shock wave, it radiates an appreciable amount of seismic energy because of its longer duration. Since severe bubble oscillations result in poor seismographic records, measures are taken to reduce or eliminate this effect.

When the initial positive pressure pulse from an energy source reaches a free water surface, it is reflected as a pulse of opposite polarity. If the peak value of pressure in the incident positive pulse is less than 1 atmosphere (14.7 psi), the reflected pulse will be the mirror image of the incident pulse and negative in sign. This phenomenon is called rarefaction.

Appendix D

A Description of Selected Non-explosive Energy Sources
(from Falk and Lawrence, 1973)

Flexotir

Although the Flexotir system employs a 2-ounce explosive charge, it is classified as a non-explosive energy source and may be used with any conventional seismic amplifying and recording source. In use, the charge is suspended in the center of a perforated cast iron spherical shell or cage. The shell is approximately 2 feet in diameter, 2 inches thick and perforated with 13 holes slightly over 2 inches in diameter. When the charge is detonated, part of the radiated shock wave passes through the open holes and part through the iron shell. The result is a damping of the bubble oscillation. One or two cages are towed at the end of 50-foot hoses from the stern of the boat. Charges are flushed down the hoses under pressure. Good reflections from marker beds down to 20,000 feet are claimed using two units simultaneously.

Vibroseis

The Vibroseis system functions by the use of continuous energy signals rather than individual pulses. Vibrations are generated hydraulically and are directed toward the seabed by means of transducers. In operation, four transducers are usually towed behind a vessel at a depth of about 40 feet. The transducers are synchronized with a prerecorded reference signal. The reflected signals are then recorded in the conventional manner.

Hydrosein

This system generates a powerful energy wavefront by means of implosion. It is created by a massive cavitation through the action of a piston in a piston chamber. In standard usage two units are operated synchronously. Since no explosion occurs, nor is air expelled into the water, no secondary or bubble phase is created. The cycle time is approximately 10 seconds between pulses. Firing at depths of 40 feet has provided the best results.

Gas Source Seismic Profiler

This system employs a modular gas source which is used with a continuous marine profile system. Ignition of a mixture of acetylene and oxygen is accomplished by a spark plug within a rubber tube with a stiffened base. Maximum pressure exerted by the tube is about 300 psi. In operation an array of several tubes is towed behind a vessel and ignited simultaneously to produce a wave front propagating perpendicular to the axis of the array.

Dinoseis

This is a gas exploder system which may be used in shallow or deep water. The heart of the system is an expandable chamber in which a mixture of propane and oxygen is ignited. Shock waves result from rapid expansion of the chamber which takes place in about 1/500 of a second. Gases are released through an exhaust valve and indirectly vented to the surface to eliminate bubble pulses. Two models are available which are capable of generating 40,000 and 100,000 pounds of energy.

Flex-O-Gun

The Flex-O-Gun system uses a mixture of oxygen and propane which is ignited by a spark plug in a firing chamber. Shock waves are created through the action of a moveable piston. Flex-O-Gun has a 300-cubic-inch capacity and a peak pressure output of 1300 psi. It was developed primarily for use in rivers, lakes and marsh areas. Groups of four or more units, spaced to meet individual requirements, are generally used in water depths from 10 to 30 feet.

Aquapulse

Seismic energy pulses are created through the Aquapulse system by confining the detonation of a mixture of propane and oxygen in an elastic-walled container. The combustion products are vented indirectly to prevent the formation of bubble pulses. Four Aquapulse units are commonly towed in a rectangular array behind a vessel and are fired simultaneously at depths from 35 to 50 feet.

Sparker

Sparker systems operate on the principle that the discharge of stored electrical energy between two electrodes in saltwater can be used to generate acoustic energy. High voltage condensers discharge electrical energy into cables towed behind a vessel. Electrode pairs at the end of the cables conduct a high current discharge into the water, creating steam bubbles which in turn generate acoustic pulses. The system is used for continuous profiling, but penetration is limited to 50 feet.

Wire Exploder

The Wire Exploder is a modified sparker with the conversion efficiency of electrical energy into acoustical energy greatly increased. The wire explosion is the phenomenon resulting from the introduction of a very large amount of energy into a fine copper wire. When the wire is exploded under water, an initial shock pulse of high magnitude, followed by an implosion, provides an acoustic pulse. The resulting pressure is several times greater in amplitude and time duration than with standard sparkers.

Hydrosonde

Hydrosonde is a continuous seismic profiling system applicable to problems connected with marine engineering surveys and underwater mineral and oil exploration. The technique is similar to echo sounding and employs a repetitive pulsed sound source. Creation of a high-energy sound pulse may be achieved by means of a spark, ignition of gases or water displacement. The echos are received by a detector consisting of either one or any array of hydrophones.

Vaporchoc

The Vaporchoc system operates on the principle that steam can be condensed into water with a very high and rapid volume reduction. Once a steam bubble has collapsed and condensed, the medium is not subject to any further pressure which usually causes the bubble effect. During operation, steam is injected into the sea in the form of a bubble which grows as long as steam is discharged. As soon as the injection is stopped, the steam condenses and due to the effect of hydrostatic pressure, the bubble collapses completely. All the energy is converted into kinetic energy in the form of the inflowing water. Conventional shooting rate is one shot every six to 12 seconds with equal efficiency in shallow or deep water.

Par Air Gun

The Par Air Gun is a well-established and widely used marine seismic energy source. It operates by high pressure release of air directly into the surrounding medium. This provides an acoustic output in the useful range of seismic frequencies. Peak pressure output is proportional to operating pressure and roughly proportional to the square root of volume. Several models of air guns are available ranging in volume from 1,000 to 2000 cubic inches and operating pressures from 200 to 2200 psi. The output power spectrum may be synthesized in several ways: (1) by combining air guns of different chamber sizes in arrays; (2) by using time and/or space diversity in firing an array of guns; (3) by using a wave shape kit to shape the output of an individual gun. Portable air gun systems are versatile and can be used from small boats in shallow water.

Seismojet Air Gun

The Seismojet Air Gun is a portable but powerful pneumatic energy source which is used for shallow and deep-water marine exploration. The power output ranges from 3,000 to 8,000 psi at a frequency of 8 cycles per second.

Appendix E

Models for Estimating Maximum Lethal Ranges of Seismic Energy Sources

Three models were constructed for the purpose of estimating the maximum lethal ranges of: (1) high-velocity explosives, (2) low-velocity explosives, and (3) seismic air guns. Information for these graphs was taken directly from the literature reviewed. Data was taken only from those studies which stated distinct lethal distances from shot points for specific size energy sources. Points were graphed to observe possible relationships between energy sources and their subsequent lethal ranges. The objective of this effort is to enable someone using a seismic energy source to estimate the lethal distance resulting from the shot.

1. High-velocity explosives

The information regarding high-velocity explosives is highly variable. Values in the model range from 1.25 to 4000 pounds for charge weights and from 0 to 3000 feet lethal distances for these charges (Figure 8). A definite pattern is apparent for the high-velocity explosive weights with the exception of three specific incidences. Gowanloch and McDougall (1945) used bottom-placed charges of 200 and 800 pounds of 60 percent gelatin dynamite on caged fish in 18 feet of water. Charges were detonated electrically. The resulting lethal distance was 200 feet for both the 200- and 800-pound charges. They conclud that this similarity is due to the fact that, although four times as large, the power of the 800-pound blast was rapidly dissipated past 200 feet. Muth (1966) conducted tests using 2000- and 4000-pound charges of Nitrone SM and Geogel placed on the bottom at varying depths. The lethal range for the 4000-pound charge was approximately 3000 feet, but only 600 feet for the 2000-pound charge. No reason is given for the large degree of difference. Roguski and Nagata (1970) have found that under-ice detonation of 130.5 to 142.5 pound of high explosives had a maximum lethal range of approximately 550 feet. Subsequent tests using 940-pound charges had little or no effect on this lethal range. Again, no reason is given for this difference.

A regression analysis and correlation calculation was conducted on the data with the exclusion of the three previous data points. A correlation coefficient estimate of R=0.81 was obtained. This value confirms and strengthens the fact that a distinct relationship does exist between charge size and subsequent lethal range.

An estimate of the maximum lethal distance for a particular size high-velocity explosive can be simply calculated by the model (Figure 8). This is accomplished by locating the desired weight on the horizontal axis and following up to the maximum lethal range estimate line. Follow this over to the vertical axis and obtain the lethal distance estimate (in feet). To be on the conservative side, the model tends to over-estimate the maximum lethal range (especially for the smaller weight charges).

2. Low-velocity Explosives

The amount of information in the literature concerning low-velocity explosives (i.e. black powder) is limited since they are rarely used today in seismic exploration due to their weaker recording qualities.

As shown by Figure 9, low-velocity explosives are relatively innocuous to aquatic marine organisms. Ferguson (1961) found that black powder charges up to 1100 pound detonated electrically, had practically no lethal effect on caged yellow perch (*Perca flavescens*). Black powder detonated with a nitrone primer produced nearly 50 percent mortality, but through subsequent testing, it was found that the nitrone primer was the lethal agent. A nitrone primer is a high-velocity explosive in itself. Black powder experiments were conducted by Fry and Cox (1953) to observe their effects on aquatic life. Their work revealed that 45- and 90-pound charges were completely harmless to fish. Observations were made on the water surface and underwater to obtain complete recovery of possible injured or killed fish, of which none were found. Hubbs and Rechnitzer (1952) found 4- to 45-pound charges of FFG and FFFG black powder to be consistently harmless to caged fish. The resistance of fish to black powder explosives was dramatically exhibited when 10 pounds of black powder exploded so close that the cage was badly damaged and partly covered with debris, and the door blown in. The two fish that failed to escape showed no signs of damage.

Consequently, as related from the literature and shown by the graph, low-velocity explosive sound sources have no lethal effect on aquatic organisms.

3. Seismic Air Guns

The use of air guns as a seismic energy source is a relatively new practice. Studies concerning the use of air guns and their possible effects on aquatic life are few in number and lacking in quality.

Experiments by Gaidry (unpub., in Falk and Lawrence, 1973) revealed that air guns were harmless to caged oysters placed in close proximity to the shots. Weaver and Weinhold (1972) used 20- and 40-cubic-inch air guns on caged coho salmon smolts (Onchorhynchus kisutch) at various distances and depths. Neither the 20- or 40-cubic-inch air gun, nor a simultaneous shooting of nine air guns totaling 240 cubic inches were harmful to salmon. Chelminski (1974) stated that in the five years PAR 300 cubic-inch air guns have been used in seismic surveys, there is an "absence" of evidence that they damage fish. Even multiple arrays of air guns with volumes of 640 to 1200 cubic inches had relatively no lethal effect.

Air guns have a moderate rise-time as with black powder (Hubbs and Rechnitzer, 1952; Jakosky and Jakosky, 1956), and it is surmised that the effects of equal pressure peaks will be similar (Chelminski, 1974). Kostyuchenko (1971) observed seismic air guns to be injurious to fish eggs. Air guns (2050 psi) damaged fish eggs to a distance of approximately 16 feet. Tests on newly hatched or adult fish were not conducted in this particular study. In conclusion, based on the previously stated facts and the data from the graph (Figure 10), seismic air guns are not lethal to aquatic life.

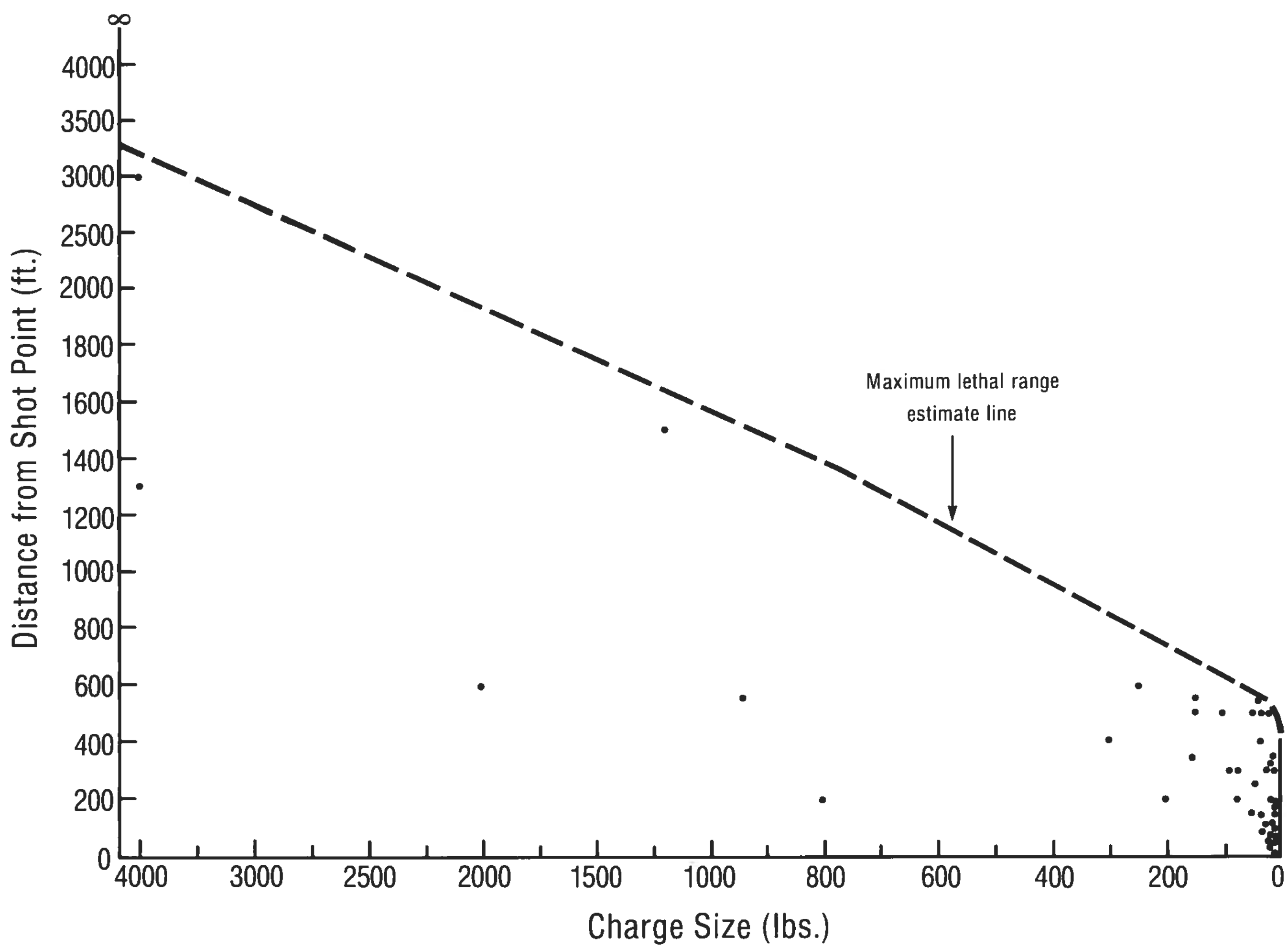


Figure 8. Model for prediction of maximum lethal range of high velocity explosives.

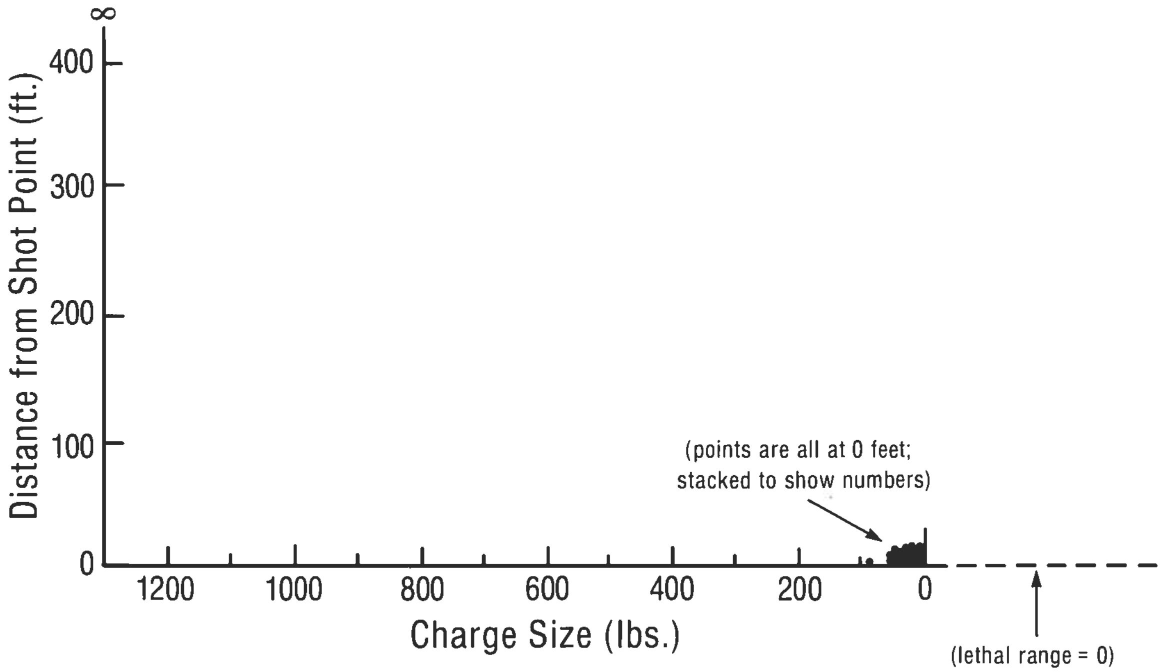


Figure 9. Model for prediction of maximum lethal range of low velocity explosives.

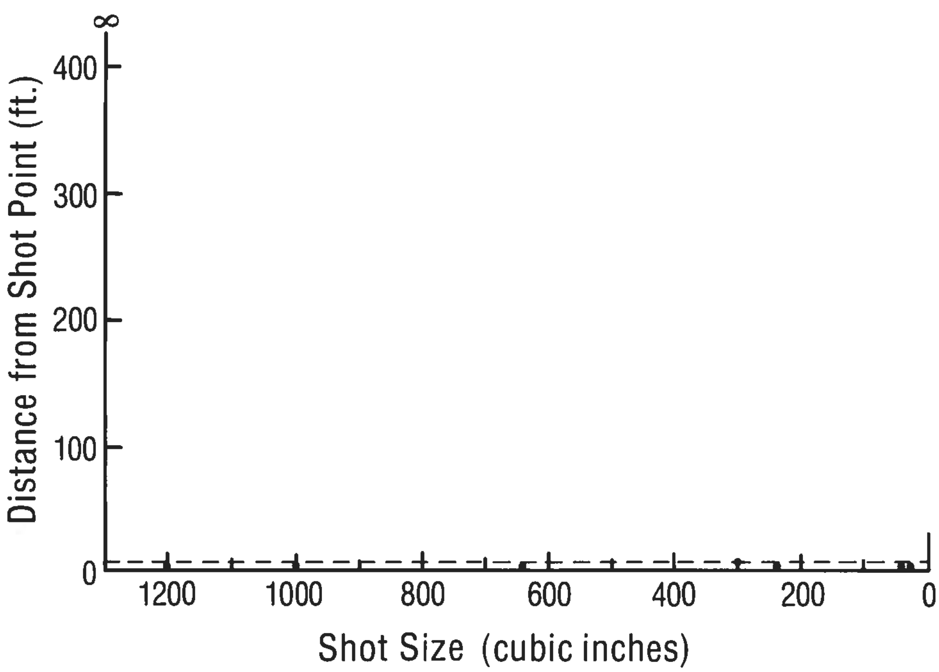


Figure 10. Model for prediction of maximum lethal range of seismic air guns.

46

The Effects of Sound Generation for
Geophysical Exploration Purposes Upon
Selected Marine Organisms:
An Annotated Bibliography

Anon. 1966. Effect of underwater explosions on fish. Australian Fisheries Newsletter. 25(3):8-9.

Tests with caged "crayfish". No injuries resulting. Noted heavy injury to barracuda and other swim bladder fish in the area incidentally. Explosives unspecified. Study site: Bass Strait; off coast of Australia.

Anon. 1976. Experimental investigations of the effects of underwater explosions on swim bladder fish, II. Naval Surface Weapons Center: NSWC/WOL/TR 76-61.

Tests conducted with white perch, spot, croaker, toadfish, white catfish, hogchoker, striped killifish, mummichog, sheepshead minnow, Atlantic menhaden, blueback herring, bluefish and oysters, using pentolite charges at various depths. Detailed injury observations.

Anon. 1978. Seismic primacord as an energy source. Technical bulletin of Primacord Seismic Services, Inc. Houston, Texas.

Consideration in designing field parameters for primacord use. Noise analysis. Size and amount required. Cord pattern length and pattern configuration. Operational considerations on land and in shallow water. Precautions and warnings.

Anon. 1983. Article concerning seismic surveys and the impact to marine life. In: Coastal Zone Management Newsletter, June 9, 1983. Nautilus Press, Inc. 1056 Natl. Press Bldg., Washington, D.C. 20045.

Article concerning the conflict between commercial fishermen and seismic vessels in the Santa Barbara Channel in California. Fishing industry demands include: no seismic research until independent research on effects of seismic blasts is undertaken, dumping of drill muds be prohibited, a fisheries preserve be established from 30 fathoms shoreward, shallow water traffic plans be established, and that a master plan for fish and oil development be drafted and employed.

Alperin, I. M. 1967. Marine fisheries and geophysical exploration-a review. Mass. Dept. of Nat. Res. Pub. No. 646.

Synopsis of selected studies in which black powder and high velocity explosives were used as seismic sources. Concluded "few fish killed with black powder, but because of inherent danger it is not used to any extent today". Invertebrates are beyond immediate influence of explosion. There are no apparent affects on shellfish and crustaceans. Lethal radius to fish is 100-200 yards even from detonations up to 1,200 lb of high velocity explosives. Only fish containing air bladders were killed by explosions. Summary of observations of seismic explosions in and conclusions of Oregon Fish Commission given. Comparison and summary of seismic exploration permits (State, Federal and Foreign) given.

Aplin, J. A. 1947. The effect of explosives on marine life. California Fish and Game. 33(1):23-30.

Caged croaker, kingfish, smelt, abalone and lobster at various distances from explosion. Found explosions close to shore killed more fish. Major injury was to swim bladder. Study site: Santa Barbara and Ventura area, California coast.

Baldwin, W. J. 1954. Underwater explosions not harmful to salmon. California Fish and Game. 4(1):77.

Surface observations of salmon "near" explosions. Seismic exploration using FFFG black powder charges of 45 to 90 lb weights at varying distances from shore, suspended 6 feet below surface. During and after detonation no fish kills or injuries observed or changes in behavior of king and silver salmon as well as black rockfish, blue rockfish, jacksmelt and jack mackerel. No effect on sport fishing success observed.

Baxter, L. II, Hays, E. E., Hampson, G. R and R. H. Backus. 1982. Mortality of fish subjected to explosive shock as applied to oil well severance on Georges Bank. Woods Hole Ocean. Inst. Tech. Rept. WHOI-82-54.

A very extensive bibliography of papers on underwater explosions and their effects on marine life has been collected and summarized. When exposed to blast effects, vertebrates with swim bladders or lungs that contain gas are at least on an order of magnitude more sensitive than other life. Regression analysis of several different experiments on explosive damage to fish has been combined with reports of fish concentrations and explosives used in oil well severance in order to estimate the probable extent of damage to fish populations from a limited number of severance explosions. Damage per explosion should not be significant and is probably considerably less than that caused by a one-hour tow of a bottom trawl net.

Bender, E. 1978. New techniques advance marine geophysical survey. Sea Technology. p. 10-13 and 55.

Article on the latest techniques used in geophysical surveying (up to 1978). Includes: measurements for marine geophysical surveys (echo sounding, seismic reflection, gravity data, magnetic measurements and well surveys), specialized vessel operations, offshore petroleum and gas exploration, etc. Mentions the decreased usage of dynamite as an energy source due to hazards, costs, logistics, destruction of fish and other reasons. Newer methods include: air guns, propane-oxygen flexible-wall explosive devices, "sparkers", "boomers", etc.

Bennett, R. D. 1947. Report of conference on the effect of explosions on marine life. Dept. Naval Ordn. Lab. memo 9424:1-15 (Uncl.) U.S. Navy. Oct. 1947. page 3.

Conference of ichthyologists and naval biologists concluded that explosions were not dangerous to fish because the lethal distance is very small compared to the fish's normal total distribution.

Brown, C. L. and R. H. Smith. 1972. Effects of underwater demolition on the environment in a small tropical marine cove. NUSC Tech. Rep. No. 4459.

C-4 explosives used to clear a boat launch on Cross Cay Island (east of Puerto Rico). Three blasts (50 lb, 400 lb, and 1500 lb) were detonated. Test animals included: queen triggerfish, (Balistes vetula), wrass, (Halicoeres maculipinna), and sea urchin, (Lytechinur, sp.). None were injured or killed, although "numerous small fishes" were found killed.

Chesapeake Biological Laboratory. 1948. Effects of underwater explosions on oysters, crabs and fish. Pub. No. 70. 43 p.

Tests using TNT and nitramon in Chesapeake Bay, near Solomons, Maryland. Caged organisms include: striped bass, trout, menhaden, spot, croaker, oysters, and crabs. "Crusher gauges" used to approximate maximum pressure due to explosives. Charge size ranged from 28-303 lb. Lethal range for a 30-lb charge is approximately 200 feet from blast and up to 350 feet when three successive charges are used. Principle fatal injuries included: ruptured swim bladder, spleen, and liver.

Christian, E. A. 1973. The effects of underwater explosions on swim bladder fish. NOLTR 73-103, Naval Surface Weapons Center (formerly Naval Ordnance Laboratory). White Oak, Silver Spring, MD., July 1973.

A new method is proposed for predicting the maximum ranges to which an underwater explosion will injure swim bladder fish. Observed lethal ranges. Estimates of damage zone. Excellent illustrations and an extensive reference list.

Christian, E. A. 1973. Mechanisms of fish-kill by underwater explosions. In: G. A. Young, compiler Proceedings of the first conference on environmental effects of explosives and explosions. Naval Ordnance Laboratory Report. NOLTR 73-233.

Presents details of explosion effects on fish. Explains the physiological effects produced in fishes exposed to underwater explosions. Presents a model to predict fish mortality that is dependent upon certain assumptions of lethal peak pressure.

Coker, C. M. and E. H. Hollis. 1950. Fish mortality caused by a series of heavy explosions in Chesapeake Bay. Journal of Wildlife Management. 14(4):435-444.

Summary of fish injury and mortality from a series of explosions of HBX explosives conducted by the Navy off Barren Island, Chesapeake Bay, Maryland. Discussed percentages of actual fish mortality and mortality observed.

Cole, R. H. 1948. Underwater explosions. Princeton University Press, Princeton, New Jersey, USA.

Describes sequence of events in an underwater explosion, theory of the shock wave, measurement of underwater explosion pressures, shock wave measurements on surface, and other effects of pressure in the water column.

Cummings, W. C. 1983. Effects of underwater noise on marine animals (provisional bibliography). Oceanographic Consultants, 5948 Eton Ct., San Diego, CA. 92122. unpublished.

References on the effects of underwater noise on marine animals. Some have brief annotations. Most of the experimental data refer to shock waves originating with chemical explosive devices.

Day, W. C. 1974. Project Tugboat--explosive excavation of a harbor in coral. In: G. A. Young, compiler. Proceedings of the first conference on environmental effects of explosives and explosions. Naval Ordnance Laboratory Report. NOLTR 73-233.

Observations of 111 species of caged fish exposed to Aluminized Ammonium Nitrate blasts. Effects of distance and substrate condition. Fish kill observations. Primarily written from an engineering standpoint.

Dobrin, M. B. 1960. Introduction to geophysical prospecting. Section 13-3: "Seismic Operations in Water-covered Areas." p 211-217. McGraw-Hill Book Co., Inc.

Methods of shallow-water reflection, fan shooting over water (refraction), offshore operations on the continental shelves. Gulf-coast operations, including surveying with dynamite. Operations off the California coast.

Eklund, C. R. 1946. Effect of high explosive bombing on fish. Journal Wildl. Mgt. 10(1):72.

Canadian and U.S. armies conducted aerial bombings to break up ice. Biologists present to observe effect on fish life. A total of twenty-two "500-pound high explosive bombs" were dropped. Two whitefish (Coregonus couesi) were killed.

Environment Canada. 1975. Fisheries and Marine Services offshore seismic seminar, Yellow knife, Northwest Territories.

Contains eight presentations, seven by industry and one by the Fisheries and Marine Service of Environment Canada. A summary is presented of the various findings relating to observations made in Artic exploration (e.g. pressure above 40 psi are lethal to fishes). A scale for depth of buried geogel charges into the ocean bottom is given.

Ewing, M. and L. Engel. 1962. Seismic shooting at sea. Scientific American. May 1962:116-126.

Explains seismic exploration methods for oil search used in 1962.

Falk, M. R. and M. J. Lawrence 1973. Seismic exploration: its nature and effect on fish. Environment Canada, Fish & Mar. Ser. Tech Rep Series No. CEN T-73-9.

Aquaflex detonated in 165 foot lengths on the bottom in 10 ft of water, killed fish over an area of 36,200 square feet. A 10 pound charge of 60% geogel detonated 10 ft below the surface in 15 feet of water, killed fish over an area of 25,450 square feet. In contrast, a 300 cubic inch Par Air Gun caused no direct fish mortalities. Contains many cited references concerning seismic sound sources and their effects on aquatic organisms.

FAO. Fisheries Division, Biology Branch. 1965. Effect of underwater explosives on aquatic life. A bibliography and list of experts. FAO Fisheries Circular No. 2, Revision 5. 12 p.

Ferguson, R. G. 1961. The effects of underwater explosions on yellow perch. Can. Fish. Cult. Nov. 1961 (29):31-39.

The lethal effect on fish of various explosive charges detonated underwater at 5 to 10 feet below the surface was assessed. The numbers of free fish that had been killed and which had floated to the surface were not a reliable measure of charge lethality because of variations in the abundance and distribution of free fish. Captive yellow perch held in cages at 10 feet from the surface and at the bottom at direct distances from 25 to 207 feet provided a more reliable assessment of charge lethality. Black powder when detonated with an electric squib produced fatal injuries in perch at distances up to 100 feet. The destructive effect in this latter charge was due primarily, if not solely, to the nitrone primer charge. A nitrone primer charge produced fatal injuries in nearly all fish to 50 feet and injured some to 200 feet. A twenty pound nitrone charge produced fatal injuries in nearly all perch to 200 feet. Nearly all injuries involved the swim bladder or associated tissues. Laboratory examination was used to determine fatalities.

Fish Dispersal Steering Committee. 1985. Pilot study on the dispersal of rockfish by seismic exploration acoustic signals: a joint commercial fishing/petroleum exploration industries project in cooperation with State of California and federal agencies. Report distributed by the International Association of Geophysical Contractors, Denver, CO.

This pilot study, a joint commercial fishing industry and petroleum/geophysical exploration industries commissioned project, accessed the effects of seismic acoustic signals on commercially viable rockfish plumes (aggregates).

The position of the Steering Committee that oversaw this project as to the findings of this study were as follows:

"A premise on which the pilot study was based was that the reaction of rockfish to a compressed air chamber type seismic acoustic exploration energy source would be quite distinct. In this pilot study, this was not the case. There were less distinct changes observed in the spatial distribution of rockfish plumes. However, the lack of an adequate control study precludes the interpretation of a cause and effect relationship. This pilot study was not designed to quantify more subtle changes. Nevertheless, after review of the findings and extensive discussions with both the consultant and the field participants, the Steering Committee believes that those less distinct changes that were observed require further study."

This document contains one consultants report, materials relating to the proceedings of the Steering Committee and copies of field data compiled during the study with accompaning charts and graphs.

Fisheries & Marine Service. Environment Canada. 1975. Offshore seismic seminar Yellowknife, Northwest Territories, 5/12-13/15. Environment Canada (Proc.) Ice-seismic work summary.

Meeting of industries to discuss problem of getting good seismic data from difficult areas. Canadian government regulations, past and present, problem areas, areas for research, discoveries discussed, under ice exploration.

Fitch, J. E. and P. H. Young. 1948. Use and effect of explosives in California coastal waters. California Fish and Game. 34(2):53-73.

Physical effects of explosives to fish. Includes observations of susceptibility of birds and mammals. Explosives unspecified. Stated number of injured and dead fish on bottom was negligible. Study site: Santa Barbara, Newport, and Gaviota areas of the California coast.

Foye, R. E. and M. Scott. 1965. Effects of pressure on survival of six species of fish. Trans. Am. Fish. Soc. 94(1):88-91.

Tested 6 species of freshwater fish at various pressures. 300 psi resulted in various mortality rates for the 6 species. Air bladder rupture most common injury.

Fry, D. H. and K. W. Cox. 1953. Observations on the effect of black powder explosions on fish life. California Fish and Game. 39(2):233-236.

Hercules E. P. 138 seismographic black powder was used. Had no detrimental effects on various species of fish in the area of detonation.

Gaspin, J. B. 1975. Experimental investigations of the effects of underwater explosions on swim bladder fish, I: 1973 Chesapeake Bay Tests. Naval Surface Weapons Center publication No. NSWC/WOL/TR 75-58. 74 p. (see following annotation).

Gaspin, J. B., Wiley, M. L. and G. B. Peters 1976. Experimental investigations of the effects of underwater explosions on swim bladder fish, II: 1975 Chesapeake Bay tests. Naval Surface Weapons Center. NSWC/WOL/TR-76-61.

These experiments by Gaspin (1975) and Gaspin, et al. (1976) were designed to validate a theory of damage by underwater explosions to swim bladder fish. The theory is based on the dynamics of the swim bladder under the influence of an underwater explosion shock wave. Caged fish of twelve different species were placed in the vicinity of explosions. The pressure-time history of each fish specimen was determined by dissection. Pentolite charges weighing 0.6 and 32 kg were detonated at depths of 3.0 and 9.1 meters. Fish were arrayed to depths of up to 30 meters. Six shots were fired. Fish damage and pressure-time data reported. Laboratory work to determine the time necessary for fish to acclimate to various depths in the water column is summarized. Fish with swim bladders most sensitive to explosions.

Gaspin, J. B. 1977. Naval Surface Weapons Center experiments on fish damage by underwater explosions. <u>In</u>: Proceedings of 2nd Conference on the Environmental Effects of Explosives and Explosions. NSWC/WOL/TR 77-36.

Details on various experimental work conducted by the NSWC involving detonation of underwater explosives and their effects upon fish. Includes pressure-time data and fish damage data.

Goertner, J. F. 1977. Dynamical model for explosion injury to fish. Proc. of 2nd Conf. on environmental effects of explosives, and explosions. G. A. Young, compiler. Naval Surface Weapons Center NSWC/WOL TR 77-36.

Proposes a model of fish kill by explosion. Assumes kill probability determined by dynamical oscillations of the fish's swim bladder. The dynamical response is then calculated from an underwater explosion pressure-time function.

Gowanlach, J. N. and J. E. McDougall. 1944. Louisiana experiments pave way for expanded oil research. Louisiana Conservationist 3(1):3,6.

Studies conducted on the effects of 800 lb of dynamite on caged shrimp, fish, and oysters. This project was undertaken due to a request by seismic explorers to enable them to use 800 lb of dynamite for refraction shooting. Caged organisms were placed 50, 100, 150, 200, 300 and 400 feet from detonation site. Observations were made immediately, after 24 hours, and after 48 hours. All fish (croakers) were killed out to a 150 foot distance. All shrimp survived in all cages at each distance from shot. A 50 pound limit on explosives was set until further experiments could be conducted.

Gowanloch, J. N. and J. E. McDougall. 1945. Effects from the detonation of explosives on certain marine life. Louisiana Conservationist 4(12):13-16.

Experiments were conducted using 60% gelatin dynamite on fish, shrimp and oysters: (Micropogon undulatus; Penaeus setiferus; and Crassostrea virginica).

Gowanloch, J. N. and J. E. McDougall. 1946. The biological effects on fish, shrimp, and oysters from the underwater explosion of heavy charges of dynamite. Transactions of the 11th North American Wildlife Conference.

A study of the effects of explosions from gelatin dynamite on caged white shrimp, croakers, and oysters. Study site: Gulf of Mexico. 200 and 800 lb charges used. No mortality to shrimp at 50 ft. All croaker closer than 150 feet killed.

Gowanloch, J. N. 1945. Effects of seismographic dynamite underwater explosions on marine aquatic life. La. Dept of Wildlife and Fisheries. 1st Biennial Report.

Used 200 lb and 800 lb shots of dynamite and determined the effects on shrimp, fish and oyster. Fish closer than 150 feet killed; oysters at fifty feet or greater not harmed.

Gowanloch, J. N. 1947. Further seismographic dynamite experiments. La. Wild. and Fish. Comm. 2nd Biennial Report ('46 '47).

Discussion concerning revision of lines govering seismic exploration in Louisana. Not helpful to this study.

Gowanlach, J. N. 1950. The effects of underwater seismographic explorations. Proceedings of the Gulf & Caribbean Fisheries Institute, 2nd annual: 105106.

Presentation at meeting on work done by author, finds no serious mortality from seismic charges (dynamite) on shrimp, croaker, oysters or blue crab.

Hill, S. H. 1978. A guide to the effects of underwater shock waves on Arctic marine mammals and fish. Unpublished manuscript. Pacific Marine Science Rep. 78-26. Inst. of Ocean Sciences, Patricia Bay, Sidney, British Columbia. 50 p.

The physical properties of underwater shock waves are outlined. Commonly used sound sources described (explosives, air guns). Various methods for prediction of damage to fish and mammals from underwater shock waves are described and tested against published results. A simple method is given for the calculation of safe distances and/or lethal ranges from underwater explosions for fish and marine mammals. (This method is from Yelverton, 1975.)

Hubbs, C. L. and A. B. Rechnitzer. 1952. Report on experiments designed to determine effects of underwater explosives on fish life. California Fish and Game. 38(3):333-366.

Effects of various explosives, including: 60 % gelatin dynamite hercomite, and black powder on caged and free-swimming fish. Black powder proved the least harmful.

Hubbs, C. L., Shultz, E. P. and R. L. Wisner. 1960. Preliminary report on investigations of the effects on caged fishes of underwater nitro-carbo-nitrate explosions. Data report, U. of California, Scripps Institute of Oceanography. (unpublished). In: Falk, M. R. and M. J. Lawrence. 1973. Seismic exploration: its nature and effect on fish. CENT-73-9.

Isakson, J. S. 1974. Biological effects of underground nuclear testing on marine organisms II. Observed effects of Amchitka Island, Alaska, tests on marine fauna. In: G. A. Young, compiler. Proceedings of the first conference on environmental effects of explosives and explosions. Naval Ordnance Laboratory Report. NOLTR 73-223.

Discusses kills associated with three underground nuclear tests: Longshot, Milrow and Cannikan, of marine fish, birds and mammals. Makes recommendations on relative effects of explosions.

Jehl, J. R., Jr., White, M. J. Jr., and S. I. Bond. 1980. Effects of sound and shock waves on marine vertebrates: an annotated bibliography. Fish and Wildlife Service (Biological Services) FWS/OBS/80/02.

Annotated bibliography of 25 references from 1947 to 1978 dealing with vertebrate fishes attraction and reaction to sound, acute and chronic effects of shock waves, means of scaring-off fish populations from explosive sites. Also includes some papers on same topics as related to birds. Mention of mammals.

Jokosky, J. J. and Jakosky, J., Jr. 1956. Characteristics of explosives to marine seismic exploration. GEOPHYSICS, Vol. 21, p. 969-991.

Experimental studies concerning pressure-time curves from underwater explosions. Characteristics of these curves have been related to seismic record quality and the destruction of fishes and marine life. Part of an investigation to develop an explosive which would overcome some of the disadvantages of black powder. Explosives tested include: 40% dynamite, 60% dynamite, primacord, multipulse, and black powder.

Kearns, R. K. and F. C. Boyd. 1965. The effect of a marine seismic exploration on fish populations in British Columbia coastal waters. Fish Culture Development Branch, Dept. of Fisheries of Canada, Pacific Area, Vancouver, British Columbia.

Marine seismic survey off the west coast of British Columbia by the Shell Oil Co. of Canada. Large charges (50-300 lb) of Nitrone S. M. killed more fish more frequently than light charges (5-25 lb). 419 (4.3%) of a total of 9,638 shot points exhibited a total surface mortality of 59,277+ fish (mainly herring and rockfish.).

Kemp, R. J. Jr. 1956. Do seismographic explosions affect marine life? Texas Game and Fish. 14(9):11-13.

Effects of seismographic explosions were determined under actual exploration conditions on fish, shrimp, oysters and blue crab, using Nitramon (nitro-carbo-nitrate). Location: Corpus Christi Bay and Aransas Bay, Texas coast.

Knight (1907) cited in Fitch and Young (1948). Quote: "Nor could it be said in our experience that pollock _Pollachus vireus_ were frightened away".

Kogarko, S. M., Popov, O. E. and A. S. Novikov. 1975. Underwater explosion of a gas mixture as a source of pressure waves. In: Combustion and Explosion of Shock Waves. 11(5):648-654.

A gas-mixture was used as an explosive device to create reflection waves for oil exploration. Successful results included no detrimental effects to fish and the process is repeatable.

Kostyuchenko, L. P. 1971. Effects of elastic waves generated in marine seismic prospecting on fish eggs in the Black Sea. Hydrobiological Journal. 9(5):45-48.

Injury and other effects of TNT explosives, air guns, and electric pulse generators to eggs of various fish species reported. All three exploration techniques caused egg damage.

Lavergne, M., 1970. Emission by underwater explosions. GEOPHYSICS, Vol. 35, No. 3, June 1970, p. 419-435.

Results concerning the variation of the seismic efficiency with shot conditions given: the conclusion is that the seismic efficiency of charges of the order of 100 grams can be considerably increased by dividing the charges and by shooting at depth. Two or three properly spaced 50 gram charges of dynamite, shot at a depth of about 12 m, give the same result as a single charge of about 5 to 15 kg shot at a depth of 1 m.

Linton, T. L., Landry, A. M., Buckner, J. E. and R. L. Berry (in press). The effects upon selected marine organisms of explosives used for sound production in geophysical exploration. Tx. Journal Sci. Vol. 37 No. 4 p.39-45.

Paired cages at surface and bottom at four distances from a 100 foot section of 100 grain/foot primacord detonated on the bottom in 7 ft of water. Red and black drum, white shrimp, blue crab and oysters were tested. Both species of fishes in surface cages had high survival rates; in bottom cages there was low mortality in red drum and high mortality in black drum; survival of crabs and oysters was high. Mortality appeared to be related to distance from site of detonation of the explosive.

Merritt, M. L. 1970. Physical and biological effects - Milrow Event. U.S. Atomic Energy Commission. NVO-79.

Study of nuclear underground test on Amchitka Island, Alaska. Effects on terrestial, freshwater and marine systems. Found no significant impacts on caged organisms from test. Rock greenling, Irish lords, and hairy crabs exposed to 85-170 psi, 2.5 - 5 g acceleration (8,500 - 13,000 ft from explosion). King crabs exposed to 50 psi.

Muth, K. M. 1966. A report on fish mortality caused by seismic exploration in lakes of the Northwest Territories. (unpublished). In: Falk, M. R. and M. J. Lawrence. 1973. Seismic exploration: its nature and effect on fish. CENT-73-9.

Oregon Fish Commission. 1962. Tests to investigate effects of seismic explosions on flatfish and crabs. Fish Commission, State of Oregon, Oct. 16, 1962. 20 p.

Tests on caged flatfish (Petrole Sole, English Sole, Sand dab, and Pacific halibut) and dungeness crabs to study possible lethal effects of nitro-carbo-nitrate explosives. Bottom caged specimens at 20 fathoms suffered approximately 10% mortality from a 5-16 lb charge. Tests on crabs in 8, 15, and 35 fathoms produced some dead and damaged crabs. Statistical analyses showed no significant difference in the number of dead and damaged crabs due to depth of cages, depth of shot, size of shot, or between test and central groups of cages.

Pappas, M. J. 1983. Published literature on the effects of marine geophysical operations on fish. Shell Oil Co. Information Analysis. Health, Safety, and Environment. Houston, Texas.

A compilation of 42 references concerning the effects of marine geophysical exploration on fish from 1965 to 1982. 18 are completely annotated.

Paterson, C. G. and W. R. Turner. 1968. The effect of an underwater explosion on fish of Wentzel Lake, Alberta. Can. Field-Natur. 82:219-220.

Seismic research using 2 tons of 60% nitro-carbo-nitrate explosive. Fish observed injured or killed as far as 400 meters from blast. Species included burbot, lake whitefish, trout-perch, and cisco. Mortality estimates of 100-200 of each species. Principle injuries to the fish were ruptured gas bladder and ruptured heart.

Percy, R. 1975. Fishery resources of the Beaufort Sea - implications of offshore seismic. In: Offshore Seismic Seminar, Yellowknife, North West Territories. May 12-13, 1975. Res. Mgt. Branch. Enforcement Section. Central Region. Env. of Can. Fisheries and Marine Services.

A presentation to various oil companies and fisheries biologists at Yellowknife, North West Territories, Canada. High velocity explosives are the most lethal to fish with swim bladders. Maximum horizontal lethal range of nitro-carbo-nitrate explosives for swim bladder fish is 150 feet for a 5 pound charge, 350 feet for a 10 pound charge, and 500 feet for a 25 pound charge in open water. Vertical distances are 150, 200, and 250 feet respectively for the same charges. Peak pressures between 40 and 60 psi are observed to be lethal to swim bladder fish. Multiple explosions may kill more fish by attracting them to the area because of disturbed benthos.

Rasmussen, B. 1967. The effect of underwater explosions on marine life. Bergen, Norway. 17p. In: Falk, M. R. and M. J. Lawrence. 1973. Seismic exploration: its nature and effect on fish. CEN T-73-9.

Roguski, E. A. and T. H. Nagata. 1970. Observations on the lethal effect of under ice detonations on fish. Alaska Department of Fish and Game, information bulletin No. 139.

Lethal effects and possible increased movement of resident fish due to explosions of C-4 explosives. Species included king salmon and northern pike. Injury and mortality assessment.

Ross, D. 1976. Mechanics of underwater noise. Permagon Press, New York, USA. p. 242-246.

General reference text on physics of underwater soundwave action. Section 7.10, Underwater explosions, explains physical action of sound waves produced by explosion.

Sakagucki, S., Fukahara, O., Umezawa, S., Fujiya, M. and T. Ogawa. 1976. The influence of underwater explosions on fishes. Bull. Nansei Reg. Fish. Res. Lab. 9: 33-65.

Common carp (Cyprinus carpio) and rock fish (Sebastiscus marmoratus) were used to observe the harmful effects on external and internal organs caused by underwater explosions of high velocity explosives, mainly dynamite. The serious fatal injuries included damage to the sinus venosus, liver and kidney. Rupture of the sinus venosus was the most serious fatal damage. Damage by explosion pressure on the ventral side of fish were more serious than those on other sides. This phenomena indicated that difference of fish direction against explosion source should be important in observing the symptoms on the influence to fish. (Note: abstract, figures and tables are in English, but the main text is in Japanese).

Schwartz, F. J. 1961. A bibliography - effects of external forces on aquatic organisms. Rep. to ONR, Contr. 168. Chesapeake Biological Laboratory, Solomons, MD. 85 p.

A bibliography of 1216 references grouped by subject matter. Subjects include: electricity, electronics, explosives, light, magnetism, mechanical, atomic radiation, X-ray radiation and sound. Includes a species index and an authors index. Concerning the effects of explosives on aquatic organisms, the 25 references cited are included in this bibliography.

Sieling, F. W. 1954. Experiments on the effects of seismographic exploration on oysters. Proceedings of the National Shellfish Association. 1953:93-104.

Tested the effects of explosion of Nitramon, 50 lb and 20 lb, at depths of 50 and 30 ft respectively, on oysters 20 to 250 ft from the shot. Found no significant effect on oysters from siltation, gases, or shock.

Simenstad, C. A. 1974. Biological effects of underground nuclear testing on marine organisms. Review of documented shock effects, discussion of mechanisms of damage, and predictions of Amchitka test effect. In: G. A. Young (compiler). Proceedings of the first conference on the environmental effects of explosives and explosions. Naval Ordnance Laboratory Technical Report. NOLTR 73-223.

Extensive background on underwater explosions and their effects on fish. Many references.

Skrbnitskaya, L. K. and G. S. Abarov. 1963. Observations on the death of fishes in the region of explosions. Vops. ikhtiol. 3, 2 (27).

(This report is in Russian...unable to obtain translation)

Spears, Roy W. 1980 The effects of primacord on selected marine organisms. Texas Parks and Wildlife Dept., Presentation Texas Chpt. Am. Fish Soc. Austin, TX.

100-foot lengths of primacord were detonated in Aransas Bay, Texas and effects on caged marine organisms were observed. Cages were located at the water surface and at the sediment surface (water depth-10 feet) at distances of 5, 10, 25, 50, 75 and 125 feet from the primacord. Red drum (*Sciaenops ocellatus*), black drum (*Pogonias cromis*), sheepshead (*Archosargus probato cephalus*), blue crabs (*Callinectes sapidus*) and brown shrimp (*Penaeus aztecus*) were placed in the cages. Following detonation of the primacord, 91-100% of the animals were killed in both surface and bottom cages out to a distance of 50 feet. At 75 feet, total mortality occurred only in the bottom cage. All animals at a distance of 125 feet survived.

St. Amant, L. S. 1955. Investigation of effects of seismic operations. From Sixth Biennial Rept., (1954-55) La. Wildlife & Fish. Commission.

In no case were fish kills ever determined to be great enough to statistically or significantly effect total fish production either temporarily or permanently. Offshore blasting in deep water killed few fish but blasting directly on the sea floor caused trenches to be cut which frequently fouled shrimp trawls.

Teleki, G. C. and A. J. Chamberlain. 1978. Acute effects of underwater construction blasting on fishes in Long Point Bay, Lake Erie. J. Fish. Research Bd. Canada Vol. 35:78.

Detonations of 201 Hydromex (a high explosive) of 22.7-272.4 kg per charge in 4-8 m of water in Lake Erie. Fatality radii ranged from 20 to 50 m for 22.7 kg charge to 45 to 110 m for 272.4 kg charge. Common injures to fish due to blasts were swim bladder ruptures and hemorrhaging in the coelomic and pericardial cavities. Temporally, surface mortalities were high only in the spring and late summer. Spatiallly, 47% of the total blast mortality was not visible from the water surface.

Thompson, J. A. 1958. Biological effects of the Ripple Rock explosion. Progress report of the Pacific Coast Station. J. Fish. Res. Board Can. 111:3-8.

Ripple Rock was a small island in the Seymour narrows waterway on the coast of British Columbia. The island was a navigation hazard and was to be removed by 2,750,000 lb of duPont Nitramex 2-H explosives, which would clear the waterway to a depth of 40 feet below sea level. Additional tests were conducted to survey for surface kill of aquatic life immediately after the blast and to study effects on caged fish at various distances from the site. 35 cages were set with 2 lingcod per cage. 4 "live ponds" were stocked with lemon sole. Immediately after the blast, approximately 100 rockfish were recovered from the surface. Distended bellies and ruptured air bladders were the major injuries. The recoveries from the cages indicate that fish mortality was confined to an area less than half a mile in radius from the blast.

Tiller, R. E. and C. N. Coker. 1955. Effects of naval ordnance tests on the Patuxent River fishery. U.S. Department of the Interior. Fish and Wildlife Service. Special Scientific Report. Fisheries no. 143.

Observations of fish kills caused by TNT explosions. Species killed included: spot, white perch, croaker, striped bass, and seatrout. Emphasis on marketable species. Observed kills vs. weight of charge; vs. depth of charge; and vs. species of fish. Prediction of future effects of explosive tests.

Tollifson, R. and L. D. Marriage. 1949. Observations on the effects of the intertidal blasting on clams, oysters, and other shore inhabitants. Oregon Fish Commission Research Briefs 2(1):19-23

The effects of the explosion of 50% strength dynamite on cockles, crabs and oysters was recorded. Little or no damage to surface cockles located 10 feet or further from the center. No damage to sub-surface cockles located 15 feet or further from the center. No damage to crabs located 30 feet or further from the center. No damage to oysters located 10 feet or further from the center. (The foregoing does not consider any possible after-effects such as silting.) A 50 to 75 per cent mortality of ghost shrimp was

found within 25 feet of the center. In the case of the invertebrates involved it is likely that almost all damage done by blasting is grossly physical in nature, that there is little shock or other after-effects.

Toole, C. 1983. Seismic vessels and fisheries. Marine Advisory Programs Newsletter. Sea Grant of California. Univ. of California Cooperative Extension. February, 1983.

Seismic operations. Marine seismic recording. Conflicts between seismic vessels and fishermen, including: right of way, gear conflicts, and the effects of survey equipment on fish.

Trasky, L. 1976. Environmental impact of seismic exploration and blasting in the aquatic environment. Alaska Department of Fish and Game.

Buried seismic charges. Observed compression and pulse waves. Rarefaction was the primary cause of mortality. Injury to fish from pressure changes. Egg sensitivity. Extensive bibliography.

Tyler, R. W. 1960. Use of dynamite to recover tagged salmon. U.S. Fish and Wildlife Serv., Sp. Sci. Rep. Fisheries No. 353. 9 p.

Dynamite is effective in killing salmon, and the direction and lethal range of the blast can be controlled by varying charge strength and water depth, and by the use of deflectors. 40% gelatin dynamite was used as explosive. Charge sizes were one-half stick and whole stick at depths of 2, 3, 4, 5, and 6 feet.

Wiley, M. L. and G. B. Peters. 1977. The ability of some Chesapeake Bay fishes to compensate for changes in pressure. In: Proceedings of 2nd Conference on the Environmental Effects of Explosives and Explosions. NSWC/WOL/TR 77-36.

Pressure chamber experiments on white perch (*Morone americana*) and spot (*Leiostamus xanthurus*). In both species, the rate of pressure equilibration falls as pressure increases. Includes studies involving the effects of various pressure changes on several species of fish.

Wiley, M. L., Gaspin, J. B. and J. F. Goertner. 1981. Effects of underwater explosions on fish with a dynamical model to predict fish kill. Ocean Science and Engineering, 6:223-284.

Presents calculations for predicting probable kill of fish with swim bladder from underwater explosions in deep water as a function of horizontal range and depth, assuming uniform spatial distribution. Tests with caged fish, primarily spot (*Leiostomus xanthurus*), and white perch (*Morone americana*).

Wright, D. G. 1982. A discussion paper on the use of explosives in the marine waters of the Northwest Territories. Department of Fisheries and Oceans. Fish Habitat Section.

Effects of shock waves on eggs, larvae, and adult fish of various species. Linear explosives vs. cylindrical charges and non-explosive energy sources studied. Proposes guidelines, legislation, and policy.

Yelverton, J. L., Richmond, D. R., Hicks, W., Sanders, K. and E. R. Fletcher. 1975. The relationship between fish size and their response to underwater blast. Defense Nuclear Agency Topical Report. DNA 3677T.

Eight species of freshwater fish exposed to pentolite charges in an artificial pond. Large fish less susceptible to various psi than small fish. Swim bladder and internal organ injury. Damage model calculation for predicting effects.

Yelverton, J. L., and D. R. Richmond. 1977. Relationship between fish size and their response to underwater blast. Proceeding of 2nd. conf. on the environmental effects of explosions and exploring. G. A. Young, compiler, Naval Surface Weapons Center. NSWC/WOL TR 77-36.

Determined impulses lethal to 50% (LD50) of eight species of freshwater fish using pentolite charges. Found the impulse, not the pressure was the damage parameter in freshwater surface explosions.

Young, G. A. 1974. Proceedings of the first conference on the environmental effects of explosives and explosions. Naval Ordnance Laboratory Report. NOLTR 73-223.

Collection of short papers dealing with disposal and effects of explosives and explosions in the marine environment. Contains 4 papers pertinent to fishes.

Young, G. A. 1977. Proceedings of the second conference on the environmental effects of explosives and explosions. Naval Surface Weapons Center. NSWC/WOL TR 77-36.

Collection of papers dealing with disposal of explosives and environmental impacts of Navy explosives. Contains 5 papers pertinent to fishes.

Other Sound Sources

Air guns

Barger, J. E. and W. R. Hamblen. 1980. The air gun impulsive underwater transducer. J. Acoust. Soc. Amer. 102(1): 1038-1045.

This paper discusses air gun performance as an underwater sound source (frequency range of 10 to 200 Hz). Experiments show that the accoustical efficiency of air gun sources decrease with increasing depth, falling sharply as the ambient pressure becomes a significant fraction of the initial air gun pressure. Spherical cavity and cylindrical cavity air guns. Air gun array shooting. This is a very detailed and scientific report.

Chelminski, P. 1974. The effect of dynamite and PAR AIR GUNS on marine life. Bolt Associates, Inc. Norwalk, Conn..

States that in the five years PAR air guns have been used in reflective, refractive and well-velocity surveys there is an "absence" of evidence that they damage fish. This is due to the fact that the impulse produced has a moderate rise-time and relatively low peak pressure - like black powder. Hubbs & Rechnitzer (1952) demonstrated experimentally that black powder has a very small damage radius, and they attribute this to its impulse characteristics primarilly the moderate rise-time to peak pressure. "Since air gun and black powder rise-times are similar we surmise that the effects of equal pressure peaks will be similar", that is they are not serious killers of fish.

Mott-Smith, L. M., Masraff, A. G. and V. A. Otte. 1968. The air gun as a marine seismic source. Paper presented at the annual meeting of the Society of Exploration Geophysicists, Denver, Colorado, October 1968.

Weinhold, R. J. and R. R. Weaver. Unpublished. Seismic air guns effects on immature cold salmon. Airguns.

Determines the effects of air guns used in shallow water on fish and possible lethal distance. This test indicates seismic air guns in the array configuration exert no harmful effect on fish. Suggest further testing regarding the effect of cage protection and response of other species.

Fish and Sound.

Burner, C. J. and H. L. Moore. 1963. Attempts to guide small fish with underwater sound. U.S. Fish and Wildlife Service Special Scientific Report. No. 403.

Tested feasibility of guiding brown and rainbow trout by various underwater sound producing devices, including underwater explosions, near power dams. Fish became conditioned to noise almost instantaneously. "Water Hammer", transducer; "Wampus", electro-magnetic sound projector also used as sound sources.

Chapman, C. J. 1976. Some observations on the reactions of fish to sound. Pg. 241-255 In: A. Schuijf and A. D. Hawkins, eds. Sound reception in fish. Elsevier Scientific Publ. Co., Amsterdam.

Fish showed consistant avoidance reactions to low frequency narrow band noise but were attracted by low frequency per tone stimuli. Sound reception in fish and the application to conditioning. Sensitivity of fish to sounds and the hearing mechanisms involved.

Moore, A. L. and H. W. Newman. 1956. Effects of sound waves on young salmon. United States Fish and Wildlife Service Special Scientific Report. No. 172.

Response of young salmon to sound frequencies of 5 to 20,000 cycles per second. Salmon quickly acclimated to sound changes. Natural water carries large volumes of background noise.

Moulton, J. M. and R. H. Backus. 1955. Annotated references concerning the effects of man-made sounds on the movements of fishes. Fisheries Circular No. 17. Dept. of Sea and Shore Facilities, Maine, USA.

Reference list of 25 citations, 17 of which are completely annotated. Topics include: underwater sound characteristics, hearing in fish, underwater explosions, and experiments with echo-sounders.

Moulton, J. M. 1963. Acoustic behavior of fishes In: R.G. Busnel, ed. Acoustic behavior of animals. Elsevier Publishing Co., Amsterdam. p. 655-693.

On accoustical reception in fishes. 277 references.

Richard, J. D. 1968. Fish attraction with pulsed low-frequency sound. J. Fish. Res. Board Can. 25:1441-1451.

Attempted to simulate sounds of predation in fish, random noise between 25 and 50 hz and in 100 to 200 hz. Found low-frequency pulses most effective in attracting predacious fishes off shore of Bimini, Bahamas. Herbivores not attracted.

Radio Telemetry

McKibben, J. N. and D. R. Nelson. 1982. A portable, real-time, X-Y plotting system for ultrasonic tracking of fish. Dept. of Biology. California State University, Long Beach, CA. 90840.

Minor, J. D. 1981. Diel, seasonal and home range activities of muskellunge (Esox masquinongy, Mitchell) as determined by radiotelemetry and contrasted with mark-recapture data. MSC. Thesis Dept of Zoology, U. of Toronto. 132 p.

Nelson, D. R. and J. N. McKibben. 1981. Time-release, recoverable, ultrasonic radio transmitters for tracking pelagic sharks. Proc. Third Int. conf. on Wildlife Biotelemetry, Laramie, Wyoming.

Summerfelt, R. C. 1972. Flathead catfish movements. Okla. Proj. 4-60-R. NOAA-NMFS. 76 p.